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HELSINGFORS UNIVERSITET
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Master`s thesis

Department of Geosciences and Geography

Geology

Geology, petrography and geochemistry of the Saarinen satellite open pit, Siilinjärvi carbonatite complex, Eastern Finland

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Tiivistelmä/Referat – Abstract

Siilinjärvi carbonatite in the eastern Finland is an Archaean intrusion. It is mined for the phosphorus bearing apatite used in fertilizers. Saarinen open pit is a satellite mine of the main Särkijärvi open pit. Siilinjärvi carbonatite is the lowest grade apatite ore in the world being excavated and the largest industrial mineral mine in Finland with approx. 11 Mt ore mined yearly making up almost 70 percent of the industrial minerals mined in Finland.

The Siilinjärvi carbonatite is a north-south trending and nearly vertical intrusion within basement gneisses. The complex consists of a continuous rock series between end members of nearly pure glimmerite and carbonatite. During the intrusion, the glimmerite-dcarbonatite has metasomatically altered the adjacent country rocks resulting a fenite halo of varying thickness.

The purpose of this M. Sc. thesis was to produce a geological map and study the petrography and geochemistry of the rock types of the complex in the Saarinen area.

The bedrock surface of Saarinen open pit area was mapped in detail with a GNSS receiver and data was edited with LeapFrog, ArcMap and QGIS. 24 rock samples were collected and thin sections were prepared for petrographic analysis. ICP-MS analysis was made of 20 rock samples to obtain whole rock geochemical data. Sludge sampling was carried out which produced 299 samples from 51 drill holes down to maximum 24 metres from the surface. Sludge samples were analysed with ICP-OES.

Geological mapping showed that the most carbonate rich rock types of the complex are located in the middle of the complex. The different rock types of the complex are oriented along the main direction of the formation. Fenite occurs on the edge of the complex and as xenoliths within the glimmerite-carbonatite series rocks.

Petrography studies showed that nearly all of the samples shared the same mineral constitution, only the modal proportions of different minerals vary. The main minerals are phlogopite, calcite, richterite and apatite. Geochemical whole rock analysis indicated that the phosphorus content of the rocks studied is highest in the rock types containing 10-50% carbonates. The trace element and REE compositions of the samples differ from average carbonatite, especially Nb, La, Ce and Y contents are lower. The geochemical analysis of sludge samples showed that the rock types are not continuous across long depths.

Avainsanat – Nyckelord – Keywords

carbonatite, glimmerite, phlogopite, apatite, phosphorus, petrography, geochemistry, Siilinjärvi

Säilytyspaikka – Förvaringställe – Where deposited

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Tiivistelmä/Referat – Abstract

Siilinjärven karbonatiitti on arkeeinen intruusio Itä-Suomessa. Karbonatiittimuodostuma sisältää apatiittia, jonka sisältämää fosforia käytetään lannoitteissa. Saarisen avolouhos on Särkijärven päälouhoksen satelliitti. Siilinjärven karbonatiitin apatiittipitoisuus on mailman matalin tuottannossa olevista apatiittikaivoksista ja se on Suomen suurin teollisuusmineraalikaivos. Siilinjärvellä louhitaan apatiitia sisältävää kiveä 11 Mt. vuodessa, joka on lähes 70% Suomen vuotuisesta teollisuusmineraalien tuotannosta.

Siilinjärven karbonatiitti on pohjagneissiin intrudoitunut, pohjois-etelä suuntainen ja lähes pysty muodostuma. Kompleksi käsittää glimmeriitti-karbonatiitti sarjan kivilajeja jatkuvana seossarjana lähes puhtaasta glimmeriitistä puhtaaseen karbonatiittiin. Karbonatiittia ympäröivät kivet ovat metasomaattisesti muuntuneet glimmeriitti-karbonatiitin intrudoituessa, muodostaen vaihtelevan paksuisen feniittikehän.

Tämän Pro Gradu -tutkielman tavoitteena oli kartoittaa Saarisen alueen kalliopinta ja tutkia kompleksin kivilajien petrografiaa ja geokemiaa Saarisen alueella.

Saarisen alueen kalliopinta kartoitettiin GNSS laitteella ja datan käsittelyyn käytettiin LeapFrog, ArcMap ja QGIS -ohjelmistoja. 24 kivinäytettä kerättiin petrografista tutkimusta varten. 20 kivinäytettä tutkittiin ICP-MS menetelmällä. Soijanäytteitä kerättiin 299 kappaletta 51 porausreiästä, jotka ulottuivat enimmillään 24 metriin saakka ja näytteet analysoitiin ICP-OES tekniikalla.

Kartoituksen tuloksena nähdään, että eniten karbonaattia sisältävät kivilajit ovat pääosin keskittyneet muodostuman keskiosiin ja kivilajit ovat suuntautuneita muodostuman yleisen suunnan mukaisesti. Feniittiä esiintyy muodostuman reunalla sekä ksenoliitteinä glimmeriitti-karbonatiitti sarjan kivissä.

Petrografisen tutkimuksen mukaan lähes kaikki näytteet kompleksin eri kivilajeista sisältävät saman mineraalikoostumuksen, mutta mineraalien määräsuhteet vaihtelevat kivilajeittain. Päämineraalit ovat flogopiitti, kalsiitti, richteriitti ja apatiitti. Geokemialliset kokokivianalyysit osoittavat, että tutkimusalueen kivilajien fosforipitoisuus on korkeimmillaan kompleksin kivilajeissa, joissa on 10-50 % karbonaatteja. Näytteiden hivenalkuaine- ja REE -koostumukset eroavat keskimääräisen karbonatiitin koostumuksesta, erityisesti Nb, La, Ce ja Y -pitoisuudet ovat matalampia. Soijanäytteiden geokemiallisen analyysin mukaan kivilajijaksot ovat syvyyssuunnassa usein melko vaihtelevia.

Avainsanat – Nyckelord – Keywords

karbonatiitti, glimmeriitti, flogopiitti, apatiitti, fosfori, petrografia, geokemia, Siilinjärvi

Säilytyspaikka – Förvaringställe – Where deposited

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Kuvia 29, taulukoita 3, liitteitä 4

CONTENTS

1. INTRODUCTION

The Saarinen open pit is a satellite mine of the Särkijärvi open pit in Siilinjärvi, eastern Finland (Figure 1). The Siilinjärvi carbonatite is mined for phosphorus by Yara Suomi Oy. The definition of carbonatite by Streckeisen (1980) was that it is a magmatic igneous rock in which more than half of its volume consist of carbonate minerals. As understanding the nature and origin of carbonatites have increased, they have been described as rocks with more than 30% primary igneous carbonate because the carbonate content is less significant than the origin of the carbonatites (Mitchell 2005). Due to clarification with the terminology used at the mine and in previous research, the old 50% carbonate mineral content definition is used in this study to distinguish the carbonate-dominant member of the complex, although based on the new definition by Mitchell (2005), the members of the rock series could be named more precisely.

Carbonatites are rare and form only a minute part of the magma eruptions on Earth. The mineralogy of formations varies but the most commonly carbonatite bodies consist of calcium carbonate. The Siilinjärvi complex consists of glimmerite-carbonatite series rocks (with varying amounts of mainly glimmerite, carbonatite and richterite) containing the phosphorus-bearing apatite and adjacent fenite, gneiss and diabase dykes cutting through the formation.

This study has three main focuses: geological mapping of the bedrock surface at the Saarinen area (which later has been mined), petrography and geochemistry of the different rock types and a rough estimate of the geochemistry of approx. 24 m of the top layer based on sludge drill samples, which were sourced for trial enrichment purposes.

2. GEOLOGIC BACKGROUND

2.1. Location and background

The Saarinen open pit mine is a satellite mine of the main Särkijärvi pit owned by Yara International ASA and is located near the town of Siilinjärvi, some 30 km north of Kuopio in eastern Finland.

Figure 1. A map of Finland showing the location of Siilinjärvi (Geological Survey of Finland 2020)

The Siilinjärvi carbonatite is an apatite bearing igneous Archaean carbonatite formation, the lowest grade apatite ore in the world being excavated. It is the largest industrial mineral mine in Finland with 11 Mt of ore mined yearly, which is almost 70 percent of the annual production of industrial minerals in Finland. Typical ore rock at Siilinjärvi contains 4-10% apatite and is virtually free of heavy metals. The ore contains for example only 0.3 ppm of cadmium (O'Brien et al. 2015).

The ore was found coincidentally in 1950 when a railroad from Siilinjärvi to Juankoski was being built. A sample from the building site was sent to the Geological Survey of Finland for further investigation. Mining of the ore started 30 years later in 1979 and the estimation is that mining will continue to 2035 after expanding the current open pit. Further mining would require new deposits of economical grade. After the first results indicating an economically potential industrial mineral deposit, the area was investigated for carbonate potential by Lohjan Kalkki Oy and Typpi Oy during 1958-1966. After this the focus was directed on the apatite content of the rock, in hopes of finding a phosphate source. The investigations were continued in 1967-1968 by Apatiitti Oy, which later merged into Kemira Oy. The research resulted economically significant apatite concentrations and finally in 1980 the production at the site started with 200 000 tons of apatite concentrate per year. Already during the same year, the production increased to 500 000 tons of apatite concentrate per year. In 2007 the operations at Siilinjärvi mine were transferred to Yara International ASA after state of Finland sold its share of Kemira GrowHow. The production has increased during the history of the mining site and production at Saarinen satellite open pit started in 2012. Total mining of today is 20 000 000-30 000 000 tons per year of which ore is 11 000 000 (Yara Suomi Oy 2020), making side rocks roughly half of the tonnage yearly.

The phosphate ore from the Siilinjärvi mine is processed locally at the site. Initially the ore is concentrated and moved to the phosphoric acid production plant by vehicles. In the process of making phosphoric acid, nitric acid is used to dissolve the apatite off the rock. The grade of the source rock is announced as a % P_2O_5 with an average of approximately 4% P_2O_5. Apatite is then enriched with a flotation separation process ending up being 36,5 % P_2O_5. The early output is 1 000 000 tons of apatite concentrate (Yara Suomi Oy 2020). The yield of the processing plant is 90% apatite enrichment of which 80% is used in the process of making phosphoric acid, the main end product of Siilinjärvi mine. Side products from the plant are calcite, mica, gypsum, calcinate (iron oxide), fluorosilicic acid (H_2SiF_6) and process heat, that is processed into electrical energy locally at the factory's own power plant and used as heat energy for residents of Siilinjärvi town. Waste rock is grinded into gravel and is used primarily on building dams for the tailings.

2.3. Geologic setting

The Siilinjärvi carbonatite complex occurs within the Archaean Iisalmi complex (basement gneiss), with Nilsiä quartzite belt in the east, Savo schists and Karelian granites and plutonics to the south and west (Figure 2) (Eskola 1963, Puustinen 1971, Lukkarinen 2008).

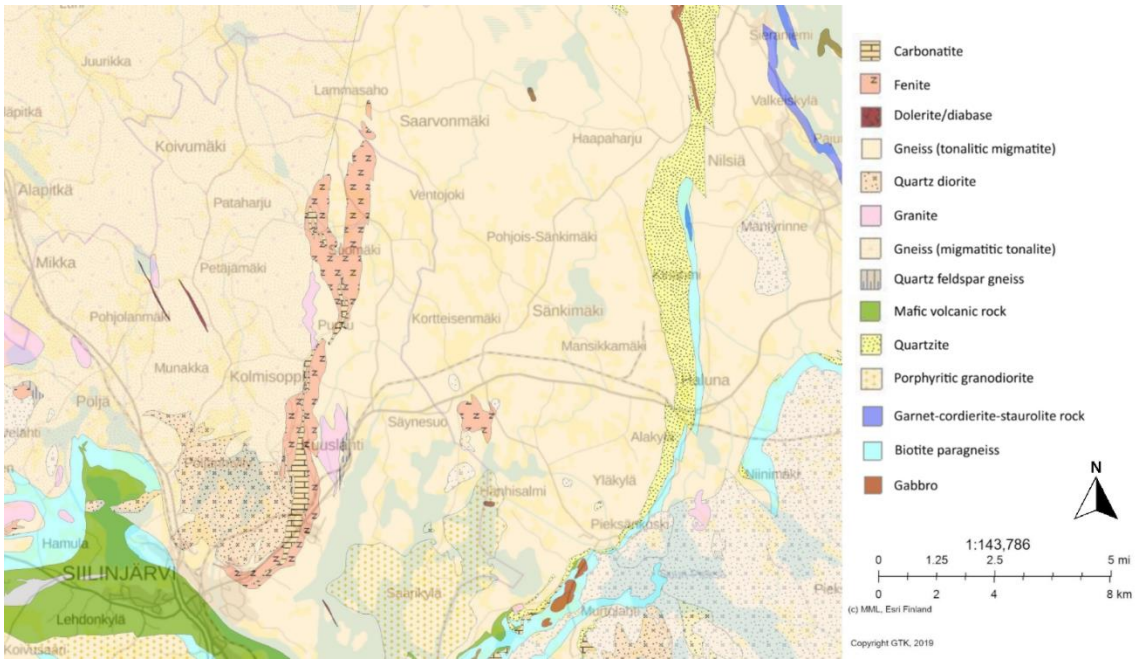


Figure 2. A geological map of Siilinjärvi carbonatite with surrounding areas (Geological Survey of Finland 2020).

The Archaean Siilinjärvi apatite-bearing carbonatite formation consist of glimmerite-carbonatite series rocks and was formed by carbonatitic magma intruding into a fracture zone in basement gneiss The glimmerite-carbonatite formation is a north-south trending, nearly vertical (approx. 70-90^{o} dip) intrusion between basement gneisses and granites (Figure 3). The formation is 16 km long in south-north direction and 1.5 km at widest in east-west direction with surface area of 14,7 km^2 (O'Brien et al. 2005). The study area of Saarinen locates 5 km to the north of the current main open pit. The formation is 2610 ± 4 Ma old based on U-Pb zircon dating (Geological Survey of Finland 1978). These Archaean basement gneisses and the carbonatite complex have gone through at least two stages of metamorphism and deformation, an amphibolite-granulite facies deformation in

the Archaean and later deformation of the Palaeoproterozoic Svecofennian orogeny 1900 Ma ago (Lukkarinen 2008).

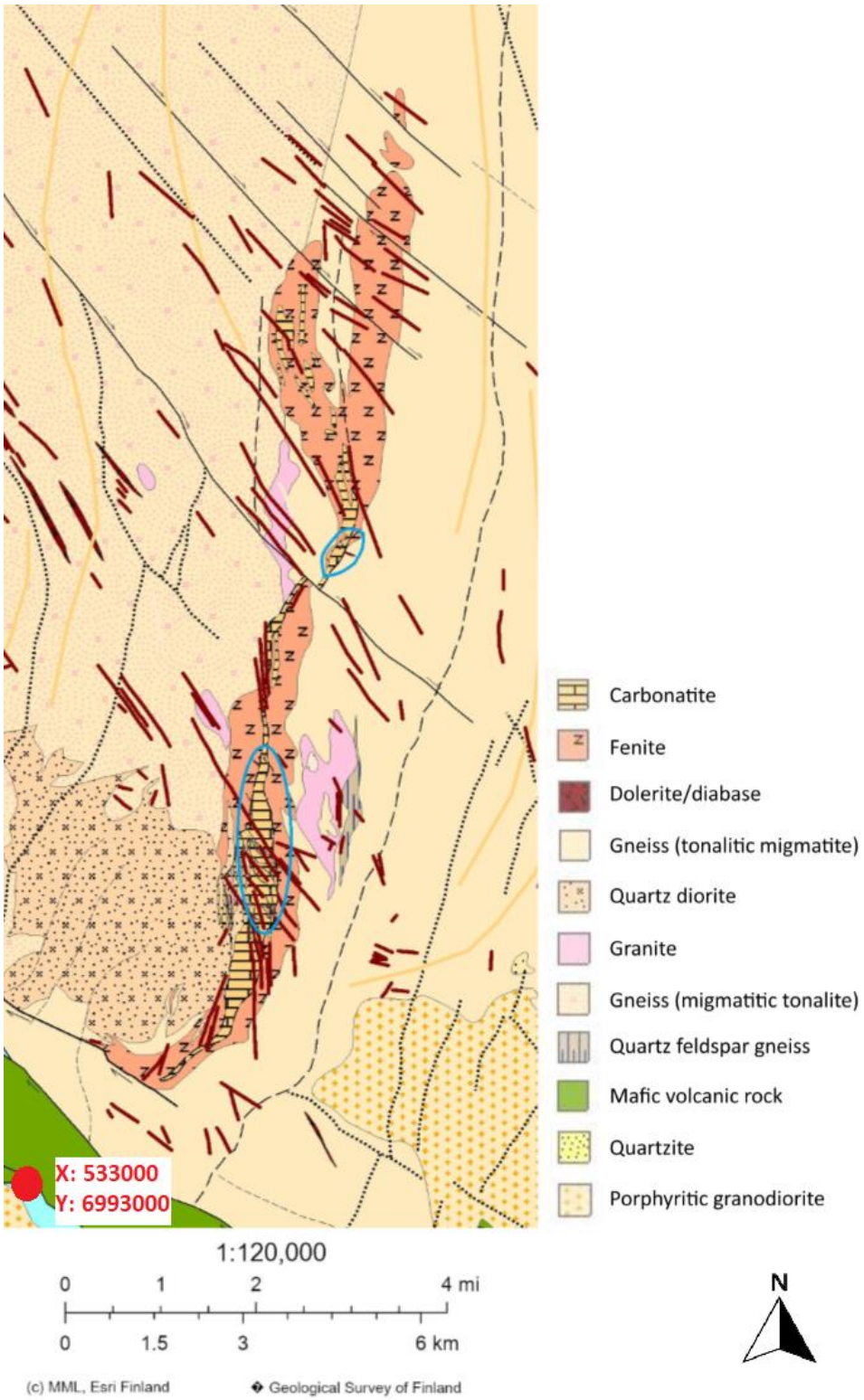


Figure 3. A map of the Siilinjärvi glimmerite-carbonatite complex. Locations of the main pit Särkijärvi in the southern part and Saarinen in the middle of the map marked with a blue line (modified after Geological Survey of Finland 2020).

The contact between the glimmerite-carbonatite intrusion and the basement gneiss has been metasomatically altered into fenite and fenite xenoliths occur also within the glimmerite-carbonatite series rocks. At first what is now known to be fenite, was assumed to be an igneous syenite intruded in between the glimmerite-carbonatites and basement gneisses (Puustinen 1971) but was later proved to be result of metasomatic alteration, fenite (Härmälä 1981, Lukkarinen 2008). At a later stage all the rock types described above have been cut through by series of dykes, most commonly diabase, but also diorite porphyry and aplite dykes have been encountered (Härmälä 1981) as well as some dark mica and amphibole rich dykes.

Although the formation has gone through later metamorphic and deformation events, the original igneous textures are usually easily observable although some distinctive shearing can be observed in the glimmeritic parts. Thermal metamorphism of the complex has not had as significant impact as dynamic metamorphism. The minimum equilibrium has been calculated to be 450°C from calcite-dolomite solvus (Puustinen 1974). Puustinen (1971) also concluded low metamorphic grade from absent carbonate-silica reactions and virtually unchanged dolomite exsolutions in calcite, which would not occur if the metamorphic grade had been higher and CO_2 could have been released. Dynamic metamorphic events are evident in the broken diabase dykes cutting through the formation. The sheering of the rocks at the margins has primarily occurred during intrusion and fortified by later movements (Härmälä 1981).

2.4. Rock types and minerals

2.4.1 Archaean basement

The oldest rock type in the Siilinjärvi area are granitic gneisses, which are the dominant basement rocks. The basement gneisses in the wider area consist of tonalite-trondhjemite migmatite gneiss and tonalite-quartzdioritic and granodioritic granitoids. At Saarinen the basement gneiss surrounds the rocks belonging to the complex (glimmerite-carbonatite and fenite) and is described as tonalite gneiss (Figure 3).

2.4.2. Glimmerite-carbonatite series rocks

Glimmerite-carbonatite series rocks are the apatite-bearing, economically valuable rocks of the Siilinjärvi carbonatite complex. It is a continuous series between nearly pure glimmerite and carbonatite. The ore consists of main minerals phlogopite and calcite and varying amounts of richterite, apatite and accessory minerals, most imporantly zircon. Other minor phase minerals accounted for the ore rocks are baddeleyite, baryte, digenite (in carbonatites at Saarinen), dolomite, magnesio riebeckite, pyrochlore, strontianite, titanite, tremolite and winchite (Hytönen 1999). The apatite rich glimmerite-carbonatite formation has been classified into four subcategories, based on an approximation of the carbonate content of the rock: glimmerite (<10 % carbonate), carbonate-glimmerite (10-25 % carbonate), silico-carbonatite (25-50 % carbonate) and carbonatite (>50 % carbonate) (Härmälä 1981). Dark glimmerite dominates the overall appearance of the formation with light coloured carbonate occurring as bands of varying thicknesses from centimetre to metre scale.

Phlogopite is the abundant mica mineral in the glimmerite-carbonatite series rocks, with chemical formulae $KMg_3(AlSi_3O_{10})(F,OH)_2$. Phlogopite appears either black, brown, reddish brown or sometimes even greenish. At Saarinen the phlogopite is mainly of the reddish-brown variety.

Carbonatite, or carbonatite proper, consists mainly of carbonate minerals, with the most abundant mineral being calcite, $CaCO_3$, some dolomite has also been recorded.

Alkali amphibole is an abundant mineral in the complex. The amphibole is richterite (Puustinen 1972), a sodium-calcium amphibole $(Ca, Na)Mg_5Si_8O_{22}(OH)_2$ and occurs mainly as blobby integrates in glimmerite-carbonatite and fibrous on sheared surfaces, but also as separate grains in carbonatite. Occasionally richterite content of the rock may exceed the amount of phlogopite. Because the mineralogical nature of the amphibole of the complex has been studied in such detail by Puustinen (1972), the more exact name richterite is used in this study.

Apatite ($Ca_5(PO_4)_3(F, OH, Cl)$, is the economic mineral due its phosphorus used in fertilizers and occurs throughout the rock series, concentrating on the rock types with less carbonates (<50 %). Average apatite content is 4-10% of whole rock and grain size varies greatly, from fractions of millimetres to tens of centimetres. Occasionally apatite occurs in such amounts that the rock type could be called “apatite rock”, a rock that contains more than 25% apatite. Due to its rare occurrence, none of the samples collected for this thesis are such “apatite rocks” even though some samples may have a very high apatite content.

2.4.3. Fenites

Fenite is a metasomatically altered rock that typically surrounds the glimmerite-carbonatite formation and is also found as xenoliths within the glimmerite-carbonatite. It is typically a bluish grey rock and the texture resembles its protolith gneiss. In earlier studies, Puustinen (1971) addresses this rock to be an intrusive syenite and explains the forming mechanism to be due to evolution of magma chamber or a different magma source than glimmerite-carbonatite. Härmälä (1982) discusses the controversy and notes that the features and relation to the adjacent rocks makes it impossible for this rock to be a product of a later intrusion rather than an alteration product of gneiss. The mineral constitution of fenite is mainly microcline, quartz, micas, apatite and clinopyroxene. Accessory phase minerals include actinolite, magnesio riebeckite and winchite (Hytönen 1999).

2.4.4. Dyke rocks

The formation has later been cut by multiple sets of dykes. The dykes run along the elongation of the formation and the most abundant dyke rock at Saarinen and the whole formation is diabase. In the central area of Saarinen there is also another type of dyke, which consist mainly of black mica and amphiboles. A set of diorite dykes in the south of Saarinen area are running perpendicular to the general trend, this dyke rock was not studied in further detail. Later movements have affected both the ore formation and dykes evident from cut dykes and other deformation features in the rocks such as shearing.

3. MATERIALS AND METHODS

3.1. Basis of sample collection

The aim of the sampling was to cover the area of the pilot open pit of Saarinen in an extent that would give an adequate result for the rock quality evaluation for mining purposes and obtain data for this study. The total area studied was approximately 10 hectares (0,1 km^2). Geological mapping and sample collection took place during summer 2011.

Sample collection was planned to obtain information of different lithologies in the area: glimmerite-carbonatite series rocks, fenite, dyke rocks and adjacent Archaean basement gneisses. Classification of the rock types in the field for mapping purposes and sample collection was based on the visual estimation of carbonate modal proportions of the glimmerite-carbonatite series or rock type of the side rocks. Evaluation of modal proportions were completely based on observational properties of the rock, mainly the colour or shade of the rock.

24 rock samples were collected for whole rock analysis and thin sections. All of the samples were prepared for thin sections that were studied with a polarised light microscope and 20 of the samples were sent to an ICP-MS analysis in ALS Finland.

Sludge samples were collected for the purpose of a trial enrichment at the plant but the chemical data received was also used for this study. A total of 299 sludge samples were collected and analysed at the mine laboratory.

3.2. Geological mapping

The rock surface mapping was carried out after the overburden was removed. Two profiles of approximately 5 metres wide were washed to observe and map the rock surface in detail. The mapping was based on lithological contacts (country rocks to the glimmerite-carbonatite series) and modal changes within the glimmerite-carbonatite series rocks. Each lithology was given a code number and the contacts were recorded

either as point sets or polygons. Glimmerite-carbonatite series rocks were subdivided into four different categories based on their visually observed carbonate modal proportion. These categories are glimmerite, carbonate-glimmerite, silico-carbonatite and carbonatite. This classification was formed by Härmälä (1981) and has been since used as the rock category names at the mine. The same division was used in the mapping of this study to make the results comparable.

Mapping was performed with a Leica GNSS receiver and the data was edited with Geovia (earlier Gemcom) Surpac, which is a 3D modelling software. LeapFrog, ArcMap and QGIS were used in digitizing the mapped data. Coordinate system used is EPSG:2393 KKJ/Finland Uniform Coordinate System. Alongside GNSS mapping, field notes were made of each point set or string. Strike/dip measurements were taken wherever possible. Also, any other features such as dykes were recorded, and their strike/dip measurements were taken when possible.

3.3. Sludge sampling

Sludge (ground rock) is a type of sampling often used at mines to receive a rough evaluation of rock types and their chemical composition. The sludge drilling provided useful information for estimation of the rock type and quality in the top 20-24 metres of bedrock as the different rock types of the complex have very distinctive characteristics, e.g. glimmerite sludge being very dark and “soft”. Sludge sampling was carried out for trial enrichment purposes and as an added advantage offered geochemical data for this study. The results of trial enrichment itself are not in focus of this study.

Sludge sampling was carried out in June and September 2011. Sludge sampling at Saarinen included 299 samples from 51 drill holes of which 31 were in the western area and 20 in the eastern area (Figure 4). Sludge samples were analysed at the mine laboratory and analysis data was used to plot a rough estimation of rock types and element abundances between 0-24 m deep.

Sludge sampling was made with a percussion drill. The drilling rig had six four metre drill tubes, hence total reach was total 24 meters. Each 4-meter drill head outputs a sludge pile that was mixed with a shovel and approximately three to four handfuls (600-1000 g) of sludge were sealed in a sample bag. The rock type was roughly estimated at the same time as the drilling rig put out the sludge. The lithologies could be observed if the total thickness of the rock type was approximately more than one meter and these were recorded on a log sheet. Identifying rock types was based on visual estimation of sludge colour and texture. Each hole was drilled to maximum 24 meters unless groundwater was encountered at higher level. Sludge sample variable maps of P_2O_5 and CaO contents were plotted with ioGAS. Location coordinates of sludge samples along analyses results are represented in Appendix 1 and Appendix 2. Field observation notes are in Appendix 3 and 4.

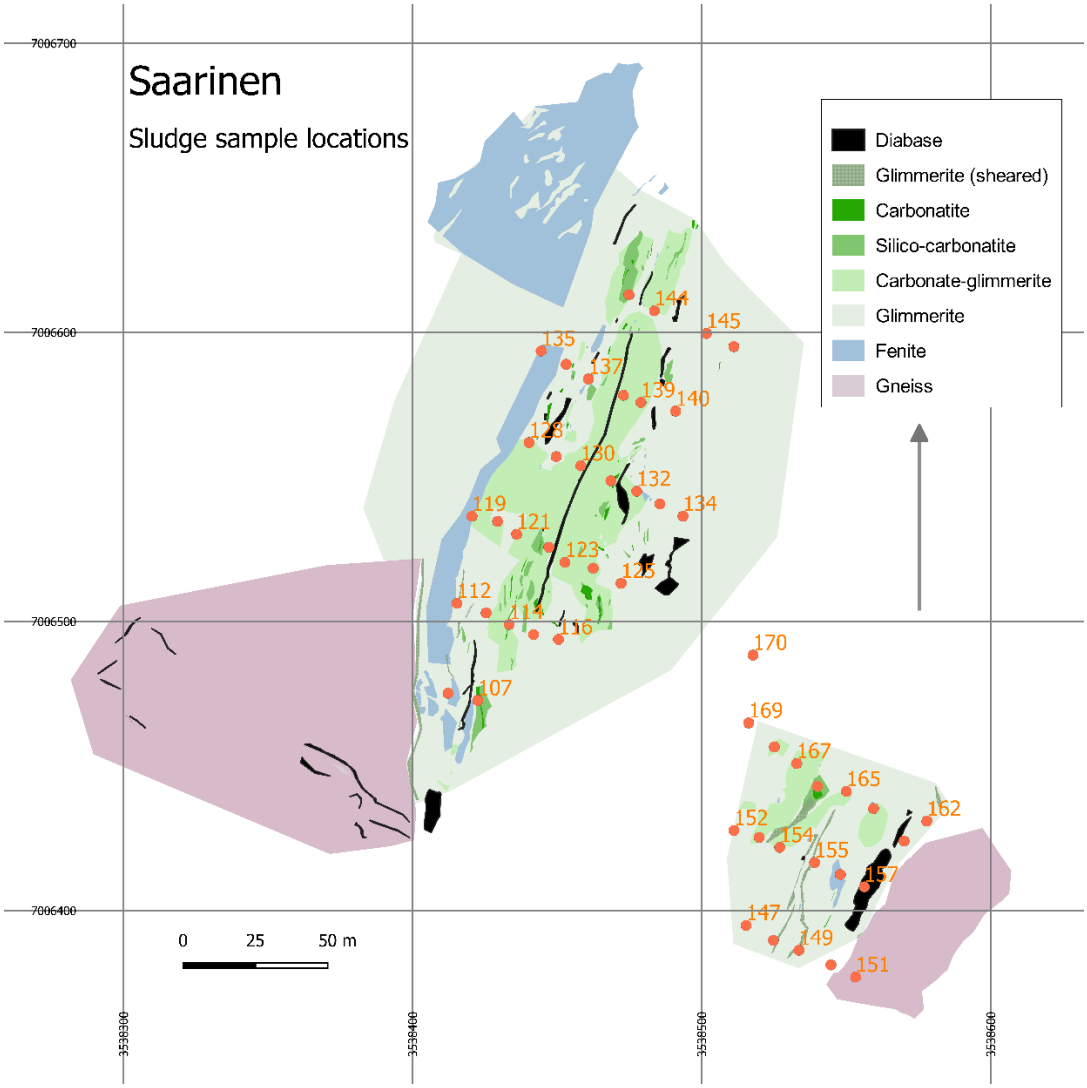


Figure 4. Sludge sample locations, Saarinen.

3.4. Chemical analysis of sludge samples

After collection, the sludge samples are first dried in the laboratory in 120-160 ^{o} and after cooling split in two with a Retsch RT 12,5 sample splitter. After adequate times of splitting the sample, 200 mg of sample and 800 mg of $Li_2B_4O_7$ is measured on a weighing boat. The sample and $Li_2B_4O_7$ is mixed and poured on a graphite crucible. The crucible is placed in 940 ^{o}C melting furnace for 15 minutes. The melt mixture is poured from the graphite crucible into a plastic beaker with 200 ml of HNO_{3-} solution. Beaker with the sample and HNO_{3-} is placed on a magnetic stirrer until the sample is fully dissolved (approximately an hour, depending on the rock type). The sample solution is filtrated into a plastic reservoir bottle. A double dilution of sample is made with deionized water for ICP-OES analysis. Elements are quantified with plasma emission spectrophotometry. CO_2 is quantified with a Leco carbon analyzer (Meri Vuorimaa, Personal communication 12.11.2020).

3.5. Petrographic studies

Total 24 rock samples representing the different rock types (glimmerite-carbonatite series rocks, fenite, granite gneiss and dyke rocks) were collected for further petrography analysis and whole rock geochemical studies. The samples were cut off from exposed rock surface with a rock saw before the start of blasting and two samples (P2011 046 and P2011 047) were cut off loose boulders in the eastern side. All sample locations were recorded (except loose boulder samples are not shown on the map) and a photograph was taken of each location before the rock block was cut off. The sample locations are represented in Figure 5. Due to the very small-scale variations between rock types in the glimmerite-carbonatite series, the two middle categories of the series (carbonate-glimmerite and silico-carbonatite) were treated as one as the variation of modal proportions of minerals are often indistinguishable. The 24 rock samples are classified as follows: 6 glimmerite samples of which 2 are of the sheared variety, 5 carbonate-glimmerite, 2 carbonatite, 3 fenite, 5 diabase, 1 “black dyke” and 2 gneiss samples.

All rock samples were prepared into polished sections at Helsinki University rock laboratory. Petrographic studies were carried out using a transmitted light microscope and each thin section was photographed in plane and cross polarized light. Hand specimens were studied and photographed alongside thin sections.

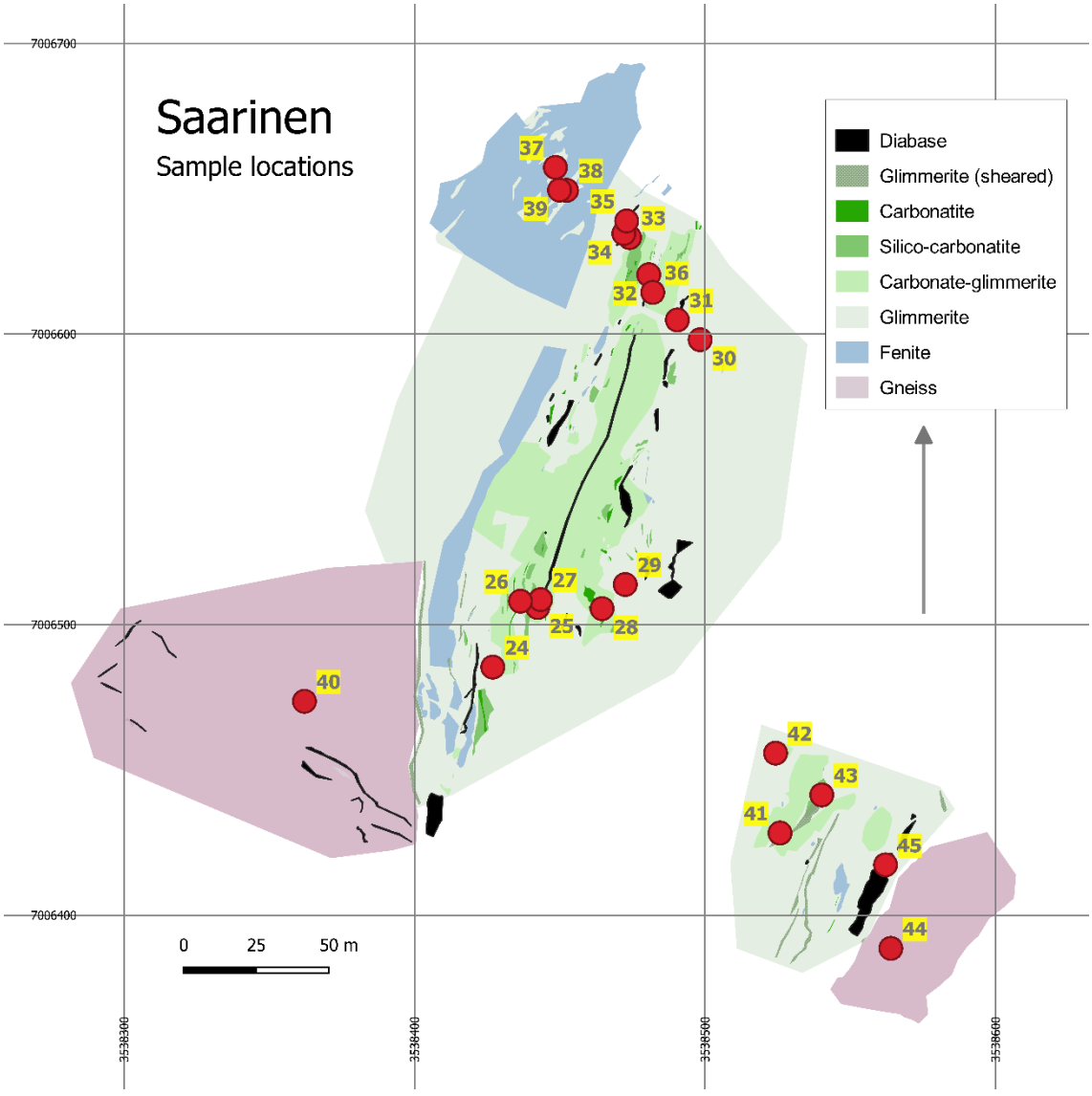


Figure 5: Sample locations, Saarinen

3.6. ICP-MS total dissolution analyses

20 samples were sent to ALS Finland for ICP-MS analysis. The number of samples was restricted due to budget available for the analysis. The samples that were left out were chosen as follows: sample P2011 033: sheared glimmerite (another sheared glimmerite

was analysed), P2011 040: gneiss (uncertainty of the rock type at collection), P2011 046: diabase and P2011 047: diabase, the two last samples were cut off loose boulders.

ICP-MS studies were carried out in ALS laboratory in Ireland. The analysis method is called ME-MS61 Ultra-trace level method using ICP-MS and ICP-AES. This method is used to detect major and trace elements in a geological sample. At first the sample is decomposed in four-acid mixture (HF-HNO_3-$HClO_4$, HCl). Four acid digestion dissolves nearly all minerals in geological samples. 0,25 g of sample is digested with perchloric, nitric and hydrofluoric acids and the residue is leached with dilute hydrochloric acid and diluted to volume. The final solution is analysed by inductively coupled plasma-atomic emission spectrometry and inductively coupled plasma-mass spectrometry. Results are corrected for spectral inter-element interferences. The list of analytes and detection limits are represented in Table 2 (ALS Finland 2019). Diagrams and tables were made using Microsoft Office Excel and JMP Pro 14.

4. RESULTS

4.1. Geological mapping

Figure 6 shows the mapped rock surface in Saarinen area, which is divided into a western and eastern areas due to a stream in between those two sides at the time of the mapping. The area near the stream could not be mapped due to soil coverage. The stream was later moved.

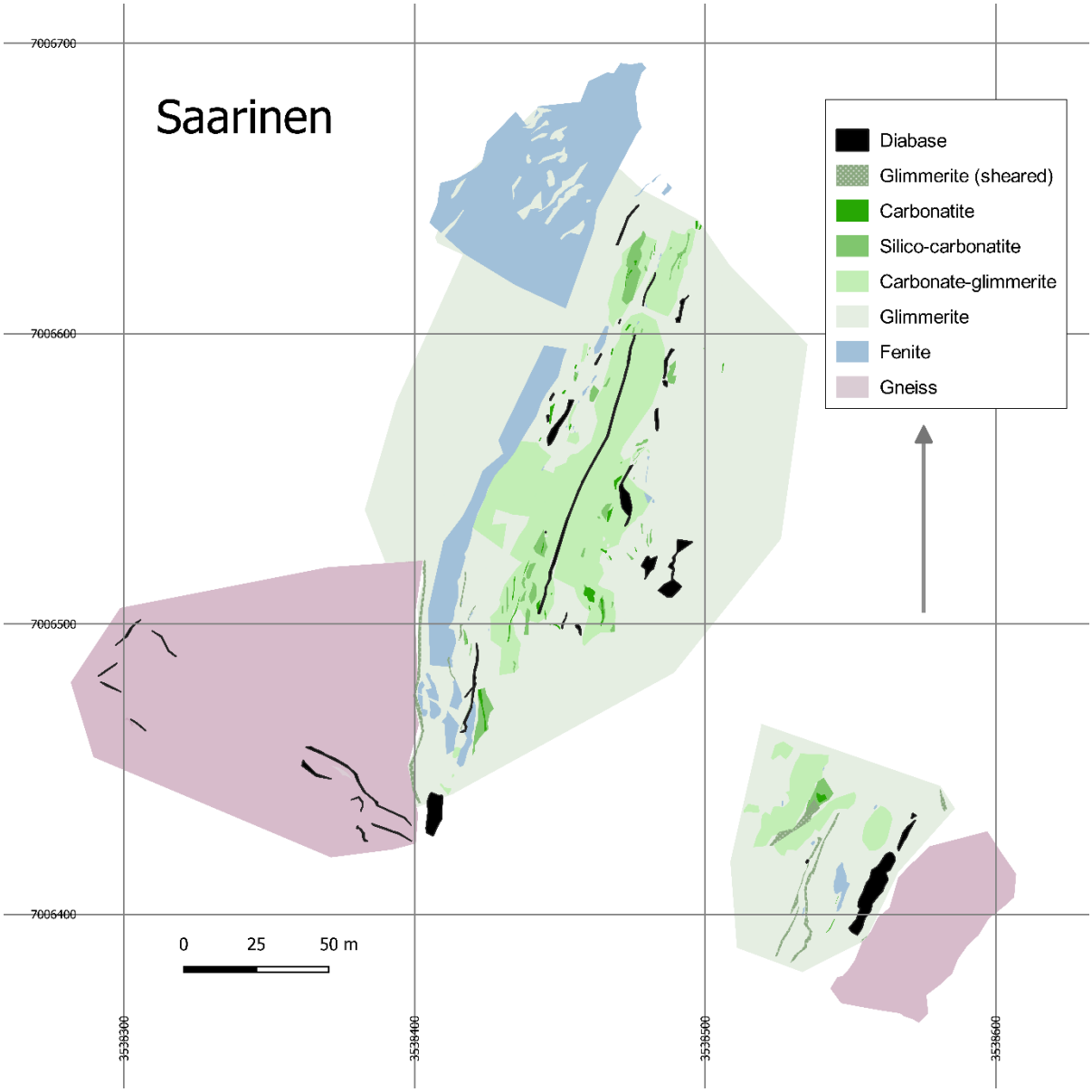


Figure 6: Geological map of Saarinen

4.1. Petrography

All of the thin sections were microphotographed, approximately half of them are presented here. In microphotographs of thin sections the plane polarised light (ppl) photo is shown on the left and cross-polarised light (xpl) photo on the right. The last two digits of the sample code are the sample numbers represented on the map (Figure 5). Mineral assemblages of samples are represented in Table 1. Abbreviations of mineral names are after the abbreviation system by Whitney and Evans (2010) as follows. I have used both

the name of the mineral series (e.g. amphibole) and a more specific name (e.g. richterite), if the identity of the mineral is known for higher certainty, based on identification and/or previous research.

Amp = amphibole
Ap = apatite
Bt = biotite (any dark mica other than phl)
Cal = calcite
Cpx = clinopyroxene
Fsp = feldpsar
Mc = microcline
Ms = Muscovite
Opq = opaque mineral
Phl = phlogopite
Px = pyroxene
Qz = quartz
Rct = richterite
Zrn = zircon

Table 1. Mineral assemblages of samples based on thin sections. Mineral abbreviation names after Whitney (2010).

sample no.	sample code	rock type	Phl	Rct	Cal	Ap	Amp	Mc	Fsp	Qz	Bt	Px	Ms	Opq	Zrn	other accessory
1	P2011 024	glimmerite	x	x	x	x								x		c'less, high relief, fractured mineral
6	P2011 029	glimmerite	x		x	x										
7	P2011 030	glimmerite	x		x	x								x		
19	P2011 042	glimmerite	x	x	x	x								x	x	
10	P2011 033	glimmerite (sheared)	x	x	x	x								x		yellow, v. high relief, straight extinction
11	P2011 034	glimmerite (sheared)	x	x	x	x								x		
2	P2011 025	carbonate-glimmerite	x	x	x	x								x		
3	P2011 026	carbonate-glimmerite	x	x	x	x										
4	P2011 027	carbonate-glimmerite	x	x	x	x										
9	P2011 032	carbonate-glimmerite	x	x	x	x								x		
18	P2011 041	carbonate-glimmerite	x	x	x	x								x	x	
5	P2011 028	carbonatite			x	x								x		
20	P2011 043	carbonatite	x	x	x	x										
16	P2011 039	black dyke			x	x	x				x					
8	P2011 031	diabase					x		x	x	x					pyrite
12	P2011 035	diabase			x				x		x					pyrite
22	P2011 045	diabase					x		x	x				x		
23	P2011 046	diabase					x		x					x		pyrite
24	P2011 047	diabase							x		x					
13	P2011 036	fenite				x		x		x	x		x		x	c'less, high relief, fractured mineral
14	P2011 037	fenite			x		x	x			x	x				
15	P2011 038	fenite						x		x	x	x				
17	P2011 040	gneiss							x	x	x			x		
21	P2011 044	gneiss							x	x	x			x		

4.1.1. Basement gneiss

The basement gneiss surrounds the complex. Two samples of gneiss were collected of gneisses on both sides of the complex, P2011 040 and P2011 044. In hand specimen Sample P2011 040 is light grey in overall colour with roughly even mix of dark and light minerals, light minerals appear greenish. It is medium grained (approx. 1-2 mm) and equigranular and has no orientation. Sample P2011 044 hand specimen is reddish brown, medium grained but has more variation in grain size than sample 040, approx. 1-4 mm. Different minerals occur similar abundances. The sample appears very slightly oriented. In thin section the samples vary from each other, most notably by the amount of biotite (greenish or greenish brown in ppl).

The main minerals of gneisses are quartz, plagioclase and biotite with accessory phases, ia. opaques. P2011 040 contains abundant mica (biotite) (Figure 7), in sample P2011 044 mica is minor interstitial phase (Figure 8). Plagioclase in P2011 040 has intergrowths of very fine grained, acicular, high relief mineral with high interference colours.

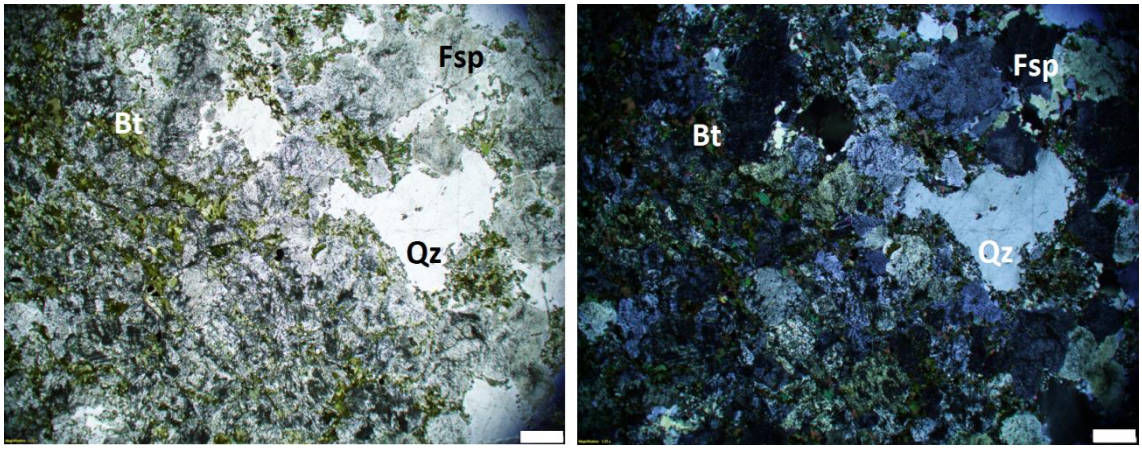


Figure 7: Sample P2011 040, gneiss from the west Saarinen area. The white bar is 1 mm.

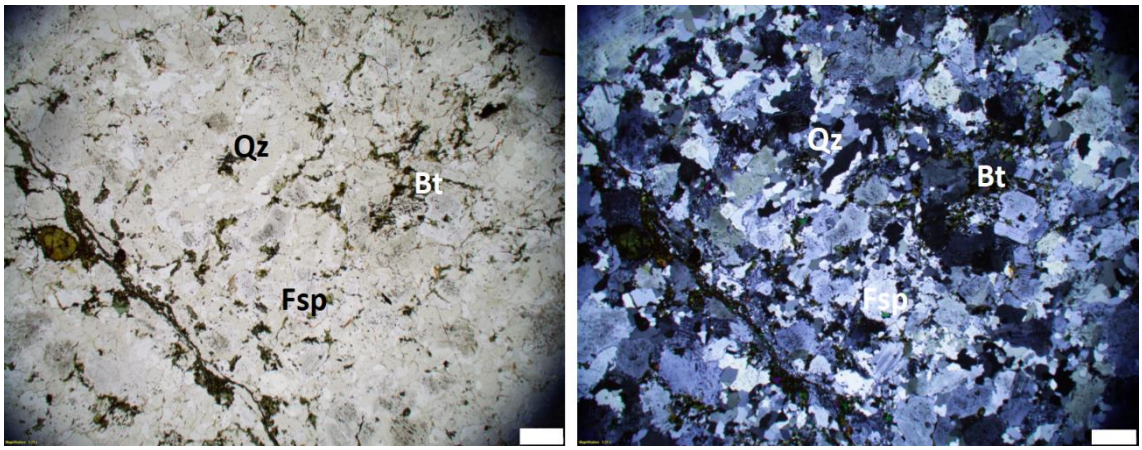


Figure 8. Sample P2011 044, gneiss from the east Saarinen area. The white bar is 1 mm.

4.1.2. Glimmerite-carbonatite series rocks

Glimmerite-carbonatite series rocks are the apatite bearing rocks. They occur as a continuous series of rocks with similar mineralogy but in varying abundances with end members being nearly pure glimmerite, consisting dominantly of phlogopite, and carbonatite, consisting nearly solely of carbonate minerals. The different rock types of glimmerite-carbonatite series are not always easily distinctive from each other but appear more as an alternating bands of rocks with varying carbonate mineral content in a dominant north-south direction. The bands are rather vague and not necessarily traceable over long distances, often only some metres at longest. The difference in appearance varies mainly based on colour, occasionally also variation in grain size. All the samples in the glimmerite-carbonatite series are rather uniform mineralogically, as almost all of

them contain the four most abundant minerals, phlogopite, richterite, calcite and apatite, at least in accessory phase.

The dominant mica in glimmerites is phlogopite. Phlogopite is found in all of the glimmerite-carbonatite series rocks. Previously the composition of mica has been studied in greater extent by Puustinen (1973). The results concluded that the dominant mica type is phlogopite along an anomalous variety tetraferriphlogopite. In glimmerite-carbonatite rocks phlogopite occurs in different shades of brown – from nearly black to dark brown and reddish brown. A trend of colour variation can be seen in association of rock type – reddish brown phlogopite seems to be mainly associated with carbonate-glimmerites and darker blackish mica with glimmerites. The colour of phlogopite also seems to be associated with deformation – darkest varieties often seem to be associated with the most deformed rocks with strong schistosity and reddish-brown mica appears in the least deformed rocks. Brown phlogopite falls in between those two. The grainsize of the phlogopite varies greatly. Occasionally large, several tens of centimetre crystals, with a characteristic platy habit, are met. In the sheared parts the grain size is dramatically reduced down to micrometre scale. The typical grain size of most rocks is around 1-5 mm.

In thin section phlogopite is typically medium brown. It has strong pleochroic colours of either greenish brown – light brown – pinkish brown or pale brownish yellow – orange brown. Pleochroism is stronger and higher up to 2nd order green birefringence colours when cut perpendicular to cleavage and 1st order greys when cut parallel to cleavage. Phlogopite has a straight extinction angle. Phlogopite shows a well-developed perfect basal cleavage and in thin section shows cleavage in grains cut perpendicular to the length of the crystal. The phlogopite crystals in thin section are usually slightly elongated along the dominant orientation. These elongated crystals also show a well-developed basal cleavage. Other crystals are more varied and anhedral in shape and show no cleavage planes, these are cut along the length. Few grains of mica were found that were distinctively different colour than phlogopite described.

Calcite is the main constituent of carbonatite endmember, also called carbonatite proper, of the glimmerite-carbonatite complex and is also very abundant in the other rocks of the series. In hand specimen it appears white or pinkish. Normally it occurs as massive grain integrates; hence grain size is difficult to distinguish. Carbonatite consists nearly solely of calcite and dolomite, other minerals (phlogopite, richterite and apatite) occur in minor amounts.

In thin section calcite occurs as colourless anhedral grains and is easily distinguishable due to characteristic lamellar twinning that display the very high interference colours (birefringence 0.172). Calcite goes to extinction parallel to cleavage planes.

Greenish blue alkali amphibole is an abundant mineral in the glimmerite-carbonatite rocks. Previous research by Puustinen (1971) reveals that the amphibole is iron rich variety ferrorichterite. In his thesis it is called richterite because no detailed mineral studies were made. Typically, the amount of richterite in glimmerites ranges between 5-30%. In places the amphibole content of glimmerite may be over 50%, this rock type could be called amphibole or richterite glimmerite, but it has not been included in the mapping due to very small-scale occurrence. Highest amounts of richterite can be found in the most deformed parts. In hand specimens amphibole appears in different habits: dark green and prismatic crystals, light blue and fibrous on sheared surface (Figure 9), and light blue and radiating in pinkish carbonatites. The prismatic habit is the most common and occurs in both separate crystals and in clusters. Overall amphibole is more common in glimmerites than carbonate-glimmerite/silico-carbonatite rocks. Occasionally richterite occurs as mineral integrates and phlogopite surrounds these richterite blobs as radiating clusters. Richterite also occurs in carbonatite and can also occur as small crystals following the rocks overall lineation.

In thin section richterite has pleochroic colours from colourless to light blue and interference colours of 1st order yellow. The coarser grains are usually prismatic and fine-grained crystals are either prismatic or acicular. Richterite has a typical inclined extinction angle of amphiboles, 50-60 degrees. Sometimes the larger amphibole crystals have a lamellae of phlogopite along cleavage planes. In addition, evidence of alteration

reactions between amphibole and phlogopite were noted, both in hand specimen and thin section.

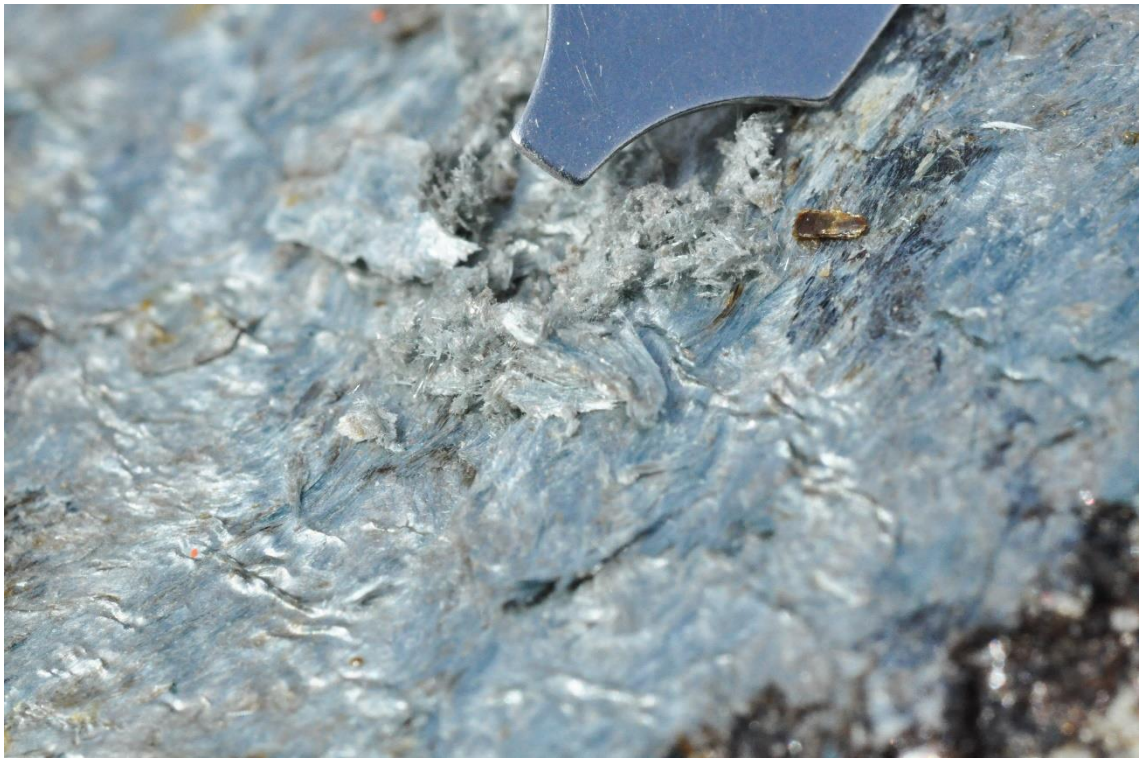


Figure 9: Fibrous richterite. Point of the metal scraper is ~3mm wide.

Apatite in the formation is the mineral of economic interest due its phosphorus content. The apatite in Siilinjärvi glimmerite-carbonatite formation is fluorapatite $Ca_5(PO_4)_3F$ (Puustinen 1971). The average apatite content of glimmerite-carbonatite series rocks is around 4-10%. Typically, the highest concentration of apatite is found in the carbonate-glimmerite/silico-carbonatite members of the rock series, apatite crystals are also found in fenite.

Apatite is a hexagonal mineral with a prismatic habit. In hand specimen apatite is translucent and seafoam green and has a vitreous lustre. It occurs most typically as anhedral to subhedral crystals of few millimetres or crystal masses and occasionally as large phenocrysts (Figure 10). Crystals up to several tens of centimetres have also been encountered in the main pit.

In thin section apatite is colourless, high relief crystals, which occur either as larger, 1-3 mm anhedral grains (similar grainsize to the groundmass) or as accessory phase acicular columnar or euhedral dipyramidal in shape.

Figure 10: Large apatite crystal in glimmerite. The pen is ~1 cm in width.

Zircon is an accessory mineral in both glimmerite-carbonatite series rocks and fenite. Typically, it occurs as small accessory grains in all of the glimmerite-carbonatite series rocks and fenite, but occasionally may be found as large euhedral crystals (Figure 11). Zircon does not show pleochroic halo when it occurs as inclusions in phlogopite.

A colourless, high relief mineral, with no cleavage (larger crystals have fractured habit) was found in samples glimmerite P2011 030 (Figure 15) and fenite P2011 036 (Figure 21). This mineral was not identified with certainty, but it resembles olivine-group minerals and could be monticellite, which has been recorded to be associated with carbonatites (Treiman 1985). This is only an uncertain interpretation as more detailed mineralogical study on these minerals was not made.

One glimmerite sample, P2011 029, contains grey, speckly looking mineral with low grey interference colours. This is most likely serpentine. Puustinen (1973) had recorded that a serpentine rich glimmerite variety was found in the northern parts of the complex.

The sheared glimmerite sample P2011 033 contained an accessory phase mineral which was not identified. Small crystals of this mineral occurred within the sheared phlogopite layers. The mineral is bright yellow with very high relief and prismatic crystals showed straight extinction.

Most of the samples contain some opaque accessories, typical opaques in the complex are ilmenite and magnetite (Puustinen 1971).

Figure 11: Euhedral zircon crystal. Point of the metal scraper is ~3mm wide.

4.1.2.1. Glimmerite

Glimmerite is a mica-bearing rock that consist of less than 10% carbonates. Glimmerites consist of mainly of phlogopite, amphibole, calcite, apatite and accessory minerals, mainly zircon, titanite and monazite. From previous research (Puustinen 1971) it is known

that the mica is phlogopite (tetraferriphlogopite $KMg_3(AlSi_3O_{10})(F,OH)$), a magnesium bearing mica of the biotite group, amphibole is blue ferrorichterite ($Na_2CaFe^{2+}_5(Si_8O_{22})(OH)_2$), carbonates are mainly calcite and some dolomite, apatite is fluorapatite ($Ca_5(PO_4)_3F$).

Overall, in hand specimen phlogopite is usually brown of different shades – most commonly being dark brown or reddish brown at Saarinen area. The grain size varies from very fine to coarse, most typically the rocks are medium grained, grainsize being 1-5mm. The finest grain size glimmerites are found in places of local shearing where the grain size is greatly reduced. Fenite xenoliths are also typically surrounded by glimmerite that is finer grained and also darker in colour. Occasionally phlogopite crystals occur as large, up to several tens of centimetres size phenocrysts (Figure 12).

Figure 12: Large phlogopite phenocryst in glimmerite. The width of the compass is 6,5 cm.

Two samples (P2011 033 and P2011 034) were collected from a location of intense and very local shearing with a strong planar alignment of micas and decreased grain size, sample P2011 033 showing crenulation (Figure 17). Even in the unsheared samples, there

may be occasional sheared layers of few millimetres wide, like in sample P2011 024, this can be called a micro shear zone.

The carbonate minerals in the less carbonate containing rocks are usually gathered in clusters that are typically elongated along the overall orientation of the rock. This gives rise to banded appearance of the formation (Figure 13).

Figure 13: Typical appearance of the glimmerite-carbonatite series rocks. Paper is 30 cm long.

In thin section the glimmerites vary in texture, grainsize, mineral abundances and colour differences in mica. The main mineral phlogopite varies in colour from greenish brown to orange brown, typically being yellowish brown in plane polarized light (ppl) and up to 3rd order interference colours in crossed polarised light (xpl). Richterite appears pale bluish grey in ppl and 2nd order interference colours.

Texturally glimmerites vary largely from each other. Occasional small-scale shearing has impacted the rocks and glimmerites as very soft rocks are intensively sheared with a decreased grain size. This is the prominent textural feature in two samples, P2011 033 and P2011 034 of which the former also shows crenulation, visible from the mica minerals

(Figure 17). In samples where there is no significant shearing, the glimmerites are rather equigranular with grainsizes of 1-5 mm.

In coarser grained specimens, both block and thin sections, replacement of richterite by phlogopite (Figure 14) can be observed. Specimens P2011 026 and P2011 042 consist mainly of richterite (Figure 16). The richterite content of the rocks varies greatly and occasionally is completely absent (Figure 15).

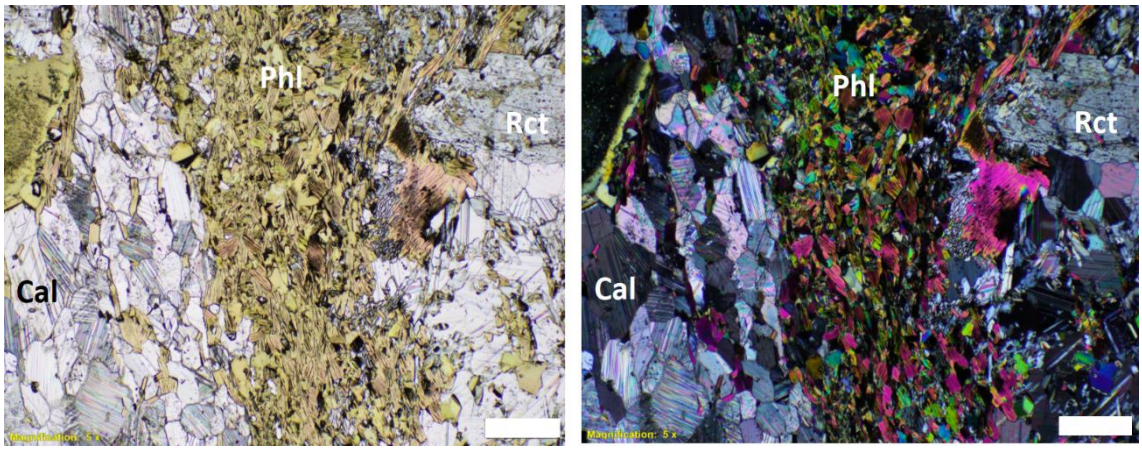


Figure 14: P2011 024 Glimmerite. Sample representing the banded texture and clustering of carbonate minerals. Phlogopite replacing richterite at the right-hand side. The white bar is 200 µm.

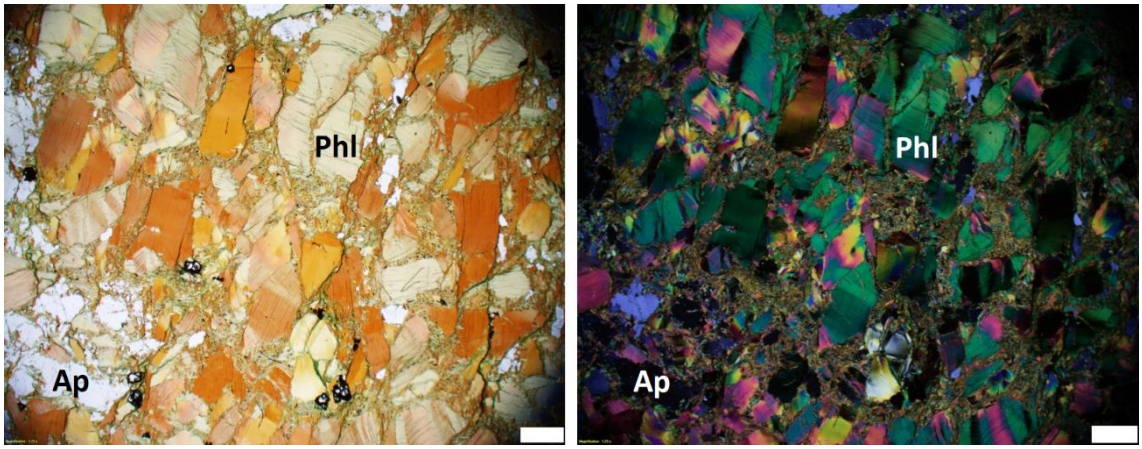


Figure 15: P2011 030 Glimmerite. Phlogopite dominated glimmerite with few calcite grains. This sample is one of the two that did not contain any richterite. The white bar is 1 mm.

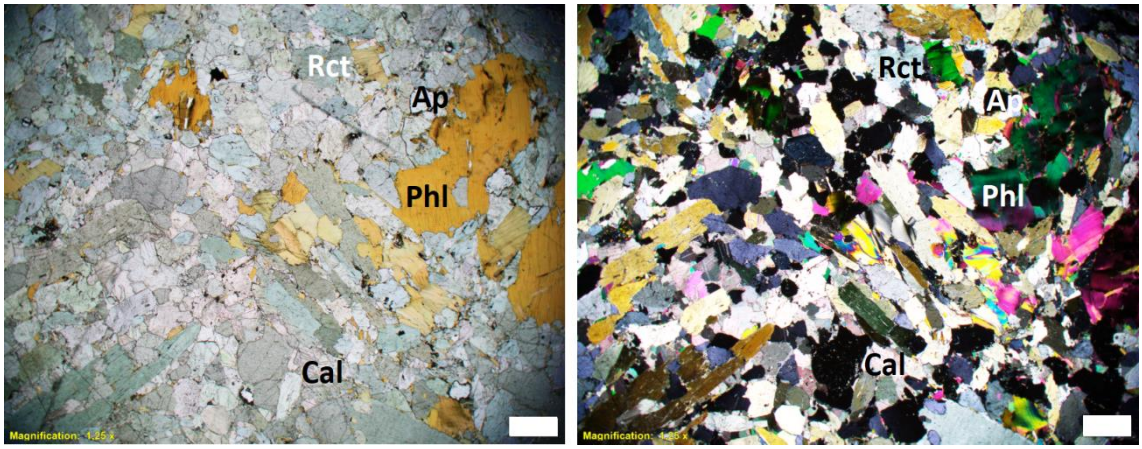


Figure 16: P2011 042 Glimmerite. Richterite rich glimmerite with phlogopite, calcite and accessory minerals. The white bar is 500 µm.

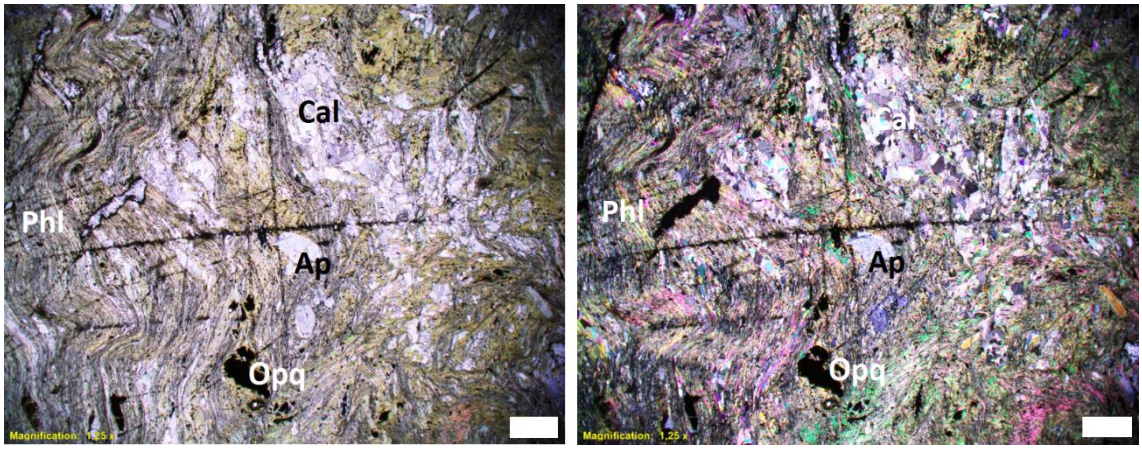


Figure 17: P2011 033 Sheared glimmerite. Very localised intense shearing with reduced grain size, mica displaying crenulation. Apatite has “survived” the shearing best, as some larger crystals remain. The white bar is 500 µm.

4.1.2.2. Carbonate-glimmerite

In the analyses and petrography of the samples in this study the carbonate-glimmerite refers to rock types with 50 % or less of carbonate minerals (subcategories carbonate-glimmerite 10-25 % and silico-carbonatite 25-50% in the mapping). Because of the small-scale variation of carbonate content, these two categories were treated jointly in sample collection. In hand specimen these rock types have similar variability in colour and grain size as glimmerites and same mineral composition, main minerals being phlogopite-calcite-richterite-apatite, only the modal proportions of different minerals vary. Texturally the carbonate-glimmerite rocks are similar to glimmerite, except sheared varieties are absent although the overall schistosity is readily visible in the outcrop,

mainly displayed by the carbonate minerals tending to gather into stripes. Carbonate-glimmerite rocks most commonly are medium grained and equigranular. Mineral assemblage is the same as in glimmerites, but the amount of carbonates is higher. Phlogopite is the main mineral and the abundances of the other minerals vary. Figure 20 shows a thin section of a typical rock in the carbonate-glimmerite category.

This group of ore rocks contain typically the highest abundances of apatite. Size of apatite grains varies greatly from fractions of a millimetre to several centimetre. Härmälä (1981) has mentioned two subcategories for apatite rich rock: apatite-glimmerite and apatite rock, of which the former resembles carbonate-glimmerite in constitution otherwise but apatite forms <15% of the rock. Apatite rock is a rock with more than 50% of apatite. Some rocks in which the apatite content was very high were encountered at Saarinen (Figure 18 and Figure 19).

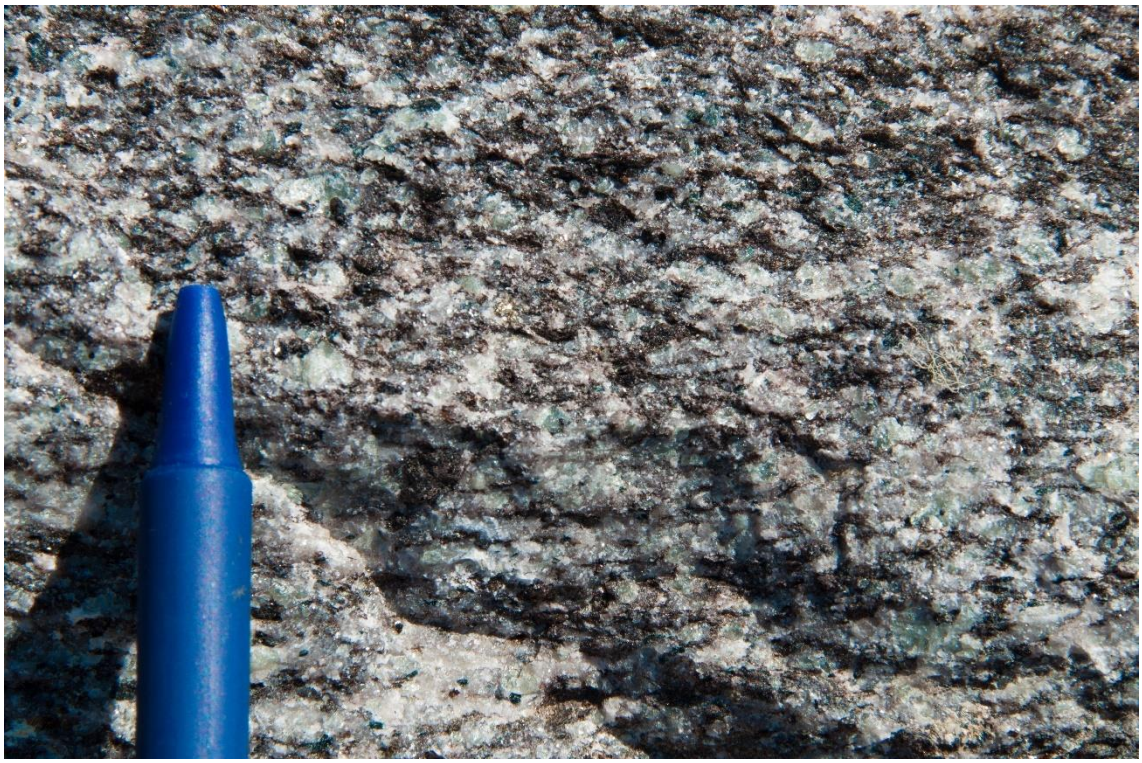


Figure 18: Apatite rock. Bluish green apatite, brown phlogopite, white carbonates.

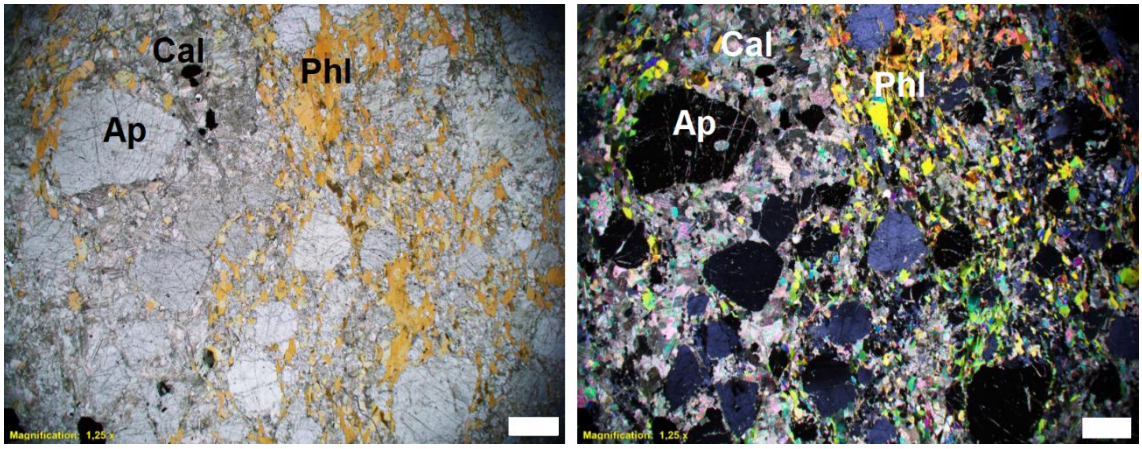


Figure 19. Sample P2011 026. Carbonate-glimmerite. Apatite rich variety of carbonate-glimmerite. The white bar is 500 µm.

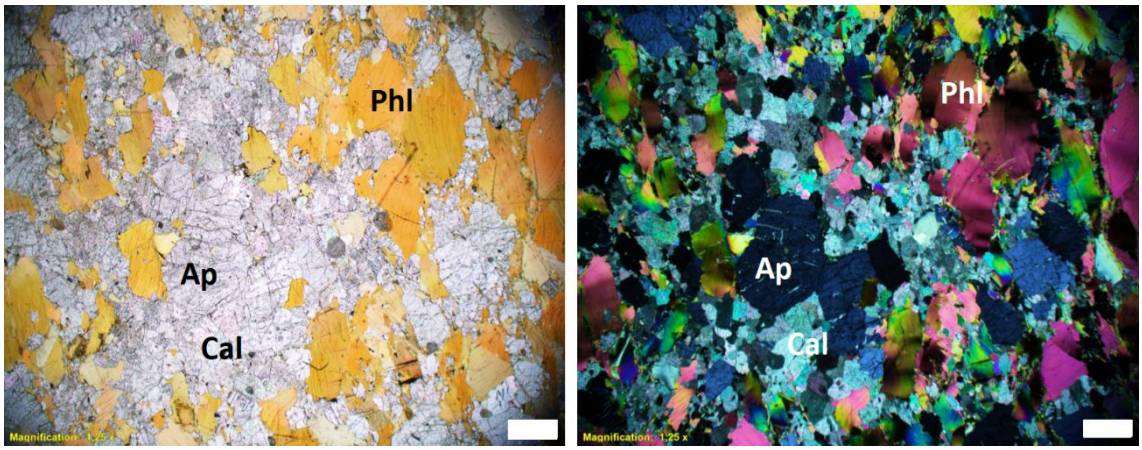


Figure 20. Sample P2011 027. Carbonate-glimmerite. A typical carbonate-glimmerite/silico-carbonatite showing the texture and grain size of the rock type. The white bar is 500 µm.

4.1.2.3. Carbonatite

Carbonatite is the carbonate-rich end member of the glimmerite-carbonatite series. The contact between carbonatite to the other rocks in the series is usually distinctive. Occasionally the contact is completely sharp but sometimes rather vague – the contact to the glimmeritic rocks occurs across few centimetres, during which the amount of phlogopite content increases away from the carbonatite. Carbonatite typically occurs as stripes or veins within the glimmeritic rocks, following the overall foliation of the lithology.

There were two collected rock samples P2011 028 and P2011 043 of carbonatite proper, both displaying a contact to the adjacent ore rock types. Carbonatites also contain the

other typical minerals in the complex – phlogopite, richterite and apatite in varying amounts and accessory phase minerals. The carbonate-rich part of sample 43 consist nearly completely of calcite (approx. 90 %) (Figure 21).

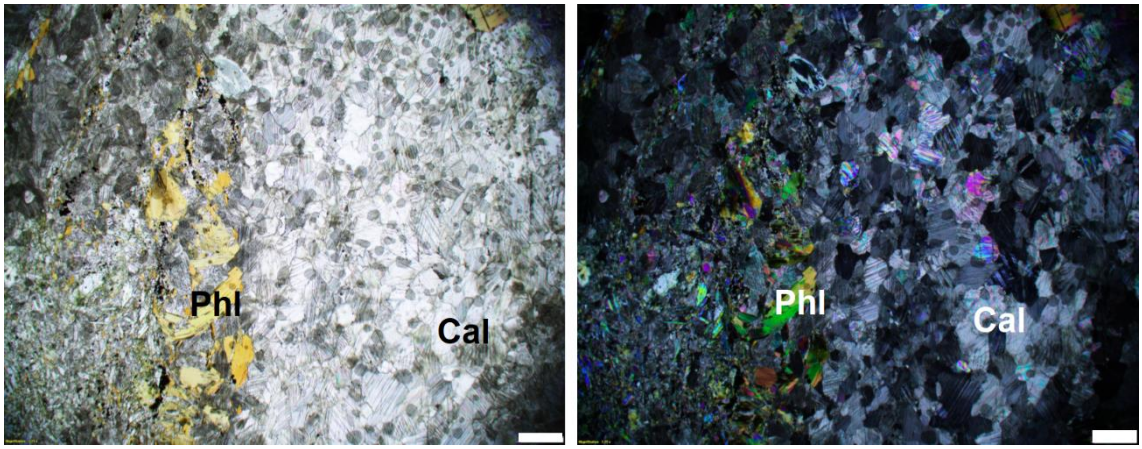


Figure 21: P2011 043 Carbonatite. Contact to glimmeritic rock on the left. The white bar is 1 mm.

4.1.3. Fenites

Fenite was first described by Brögger (1920, after Puustinen 1971). Fenite is a metasomatically altered rock type that surrounds the glimmerite-carbonatite intrusion in most places. It also occurs as xenoliths within the glimmerite-carbonatite. The contact between glimmerite-carbonatite and fenite is typically brecciated by glimmeritic rocks. Fenite enclosed xenolithic looking chunks of rock that resembled glimmerite of the ore rocks.

At Saarinen area fenite contact to gneiss is usually gradual. In places the contact is broken by local shearing, but typically the change is gradual over some metres. In the eastern edge of the mapped area fenite is missing and gneiss is at contact with glimmerite-carbonatite series rocks. In the western edge of the formation at Saarinen, the transition from fenite to gneiss occurred across a fracture zone. In other places where contact was visible, it was gradual across some metres.

The fenite xenoliths in glimmerite-carbonatite are often stretched along overall orientation of the host rock. The sizes of xenoliths vary from few centimetres to 15 metres, they are often amphibole-rich and surrounded by radiating a phlogopite rim.

Macroscopically the appearance of the fenites resemble magmatic rock. Fenite colour varies from light to dark grey, typically having a bluish or greenish tint and occasionally, but rarely, pinkish. It has an intermediate to coarse grain size and typically equigranular texture but occasionally appears striped with light and dark minerals separated into bands. In thin section fenite is dominated by microcline crystals with ragged edge, other mineral phases include amphibole, clinopyroxene, apatite, muscovite and quartz. Figure 22 and Figure 23 display two fenites of different textures.

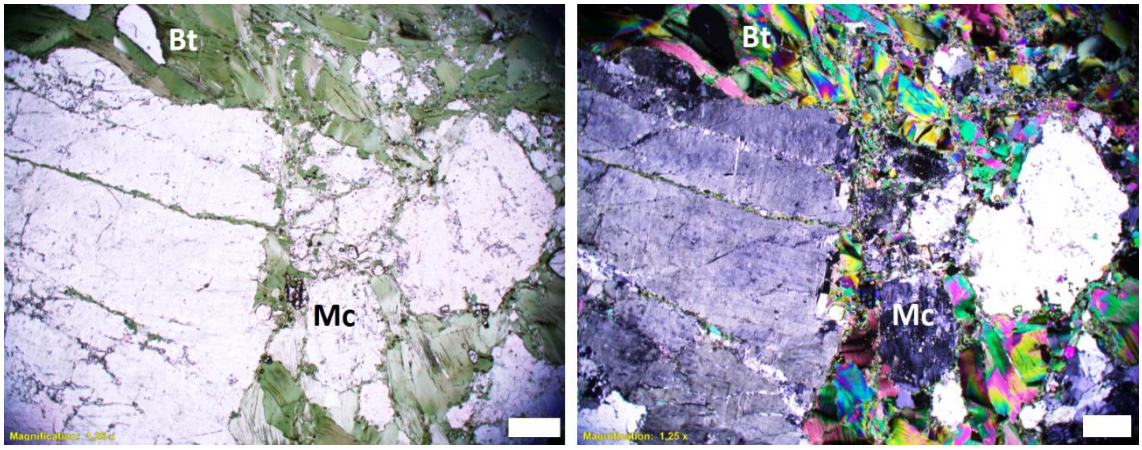


Figure 22: P2011 036 Fenite. Mica rich variety of fenite. The white bar is 500 µm.

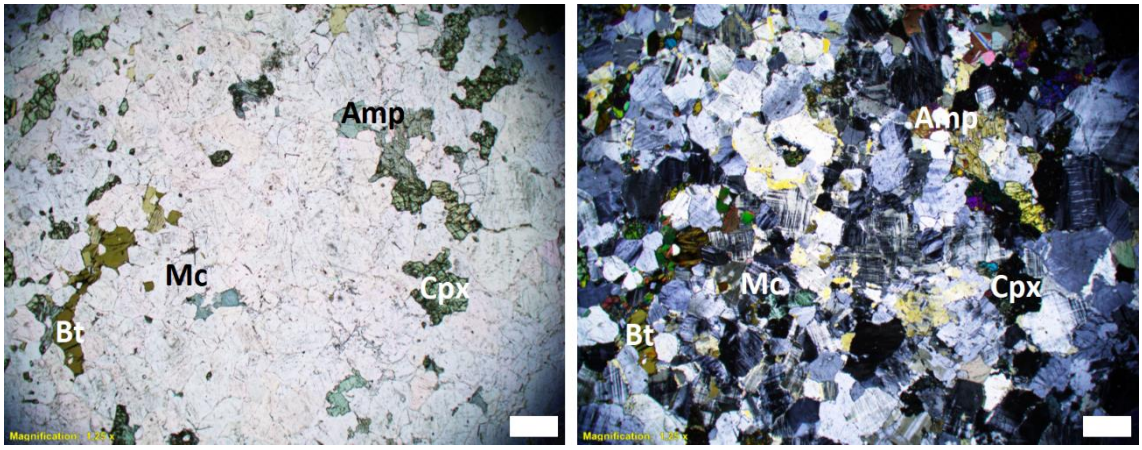


Figure 23: P2011 038 Fenite. Fine grained fenite with a typical mineral assemblage. The white bar is 500 µm.

4.1.4. Dyke rocks

The glimmerite-carbonatite formation is cut through by multiple sets of dykes. At Saarinen area three different types of dykes were encountered – diabases, a mica bearing black dyke or vein system and a diorite dyke. Diabases are abundant throughout the formation and run along the prevailing north-south direction. Two types of dykes that can be classified as diabases were encountered. Visually they have a similar very fine-grained appearance, but magnetometry studies showed that some were magnetic and some not. One vein or dyke system that consist of mainly black mica and amphibole was encountered. One diorite vein cut across southern part of Saarinen in east-west direction, this vein was not studied further and no samples were collected. Five samples of dyke rocks were collected, four of these were named diabase. The 5th sample was named ”black dyke” to distinguish it from the diabases due to its very different appearance.

In hand specimen the diabase samples are all very fine grained with some variability in mineralogy, for example sample P2011 031 seems to have a spotty appearance of lighter minerals and sample P2011 035 has visible, euhedral pyrite crystals, which are absent from other samples and sample P2011 045 is coarse grained with greenish tint and shows orientation. In thin section all of the diabase samples differ from each other texturally and mineralogically. Minerals encountered in diabases are feldspar, biotite, amphibole, calcite, apatite, quartz, pyrite and accessory phase minerals. Figure 24 displays a thin section of mica(biotite)-rich diabase.

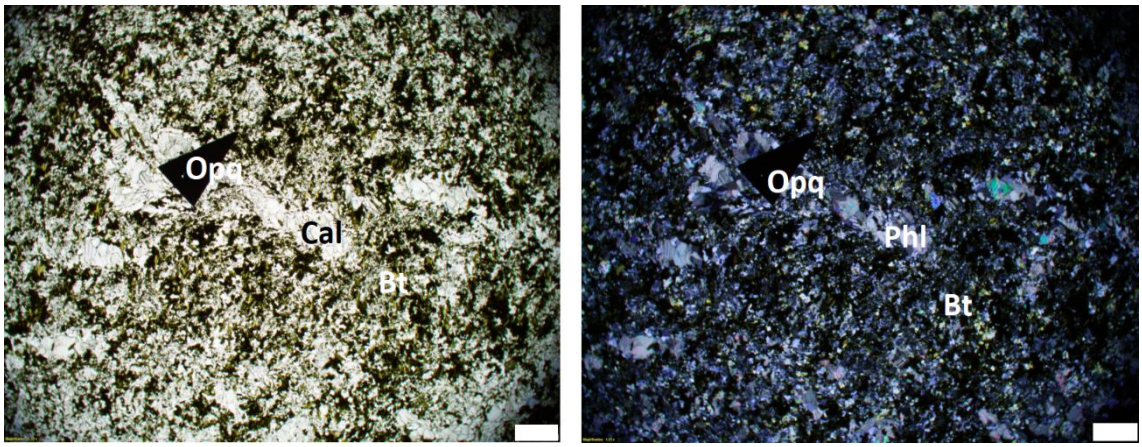


Figure 24: P2011 035 Diabase with biotite, calcite and a euhedral pyrite crystal. The white bar is 1 mm.

The “black dyke” consist mainly of black mica and amphibole. When the initial ramps were being excavated at the site in August 2011, a deeper non-weathered part of the “black vein” could be observed. Another cross-cutting dyke or a sill at about 45 degrees of similar composition was noticed at the lower level. At weathered surface the dyke seemed to consist solely of black mica but from fresh surface the rock could be observed to contain substantial amounts of green amphibole which occurred as coarse, up to 2 cm crystals. In thin section the composition and texture of the black dyke rock resembles that of glimmerite, but the mica is green in plain polarised light (Figure 25). Other minerals are amphibole, apatite and calcite. This rock resembles lamprophyre dykes.

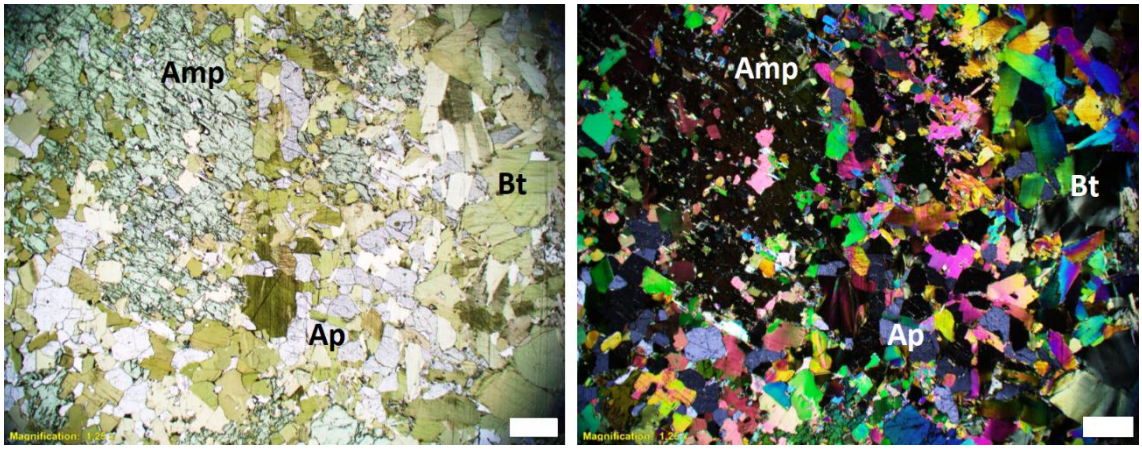


Figure 25: P2011 039 Black dyke with biotite, amphibole and apatite. The white bar is 500 µm.

4.2. Sludge samples

The rock types of the sludge samples were recorded at the field at the time of the sampling. The rock types that could be recognised were glimmeritic rocks of different colours (note taken on whether the rock was blackish brown, dark brown or reddish brown), carbonatite, fenite, diabase or gneiss. Besides colour also feeling of the powdered rock aided in determining the rock type. Due to large amount of mica, glimmerites always feel very soft and slippery and have a very distinctive colour. Rocks with harder minerals also feel rougher when ground.

Sludge sample location coordinates and analyses results are represented in Appendix 1 and Appendix 2. Depth of the sample is expressed as 0 being the ground level and 24 the maximum depth. Field observatiosn are in Appendix 3 and Appendix 4.

The P_2O_5 and CaO concentrations of sludge samples are represented in variable maps: Figures 27a-f show the sludge sample locations from Saarinen. Each variable map represents every 4 metre sample sequence. From ground level to 4 metres depth is displayed in the first diagram, 4-8 m in the second and so on. X and Y -axis contains the coordinate data. Legend for the symbols are represented separately in Figure 26.

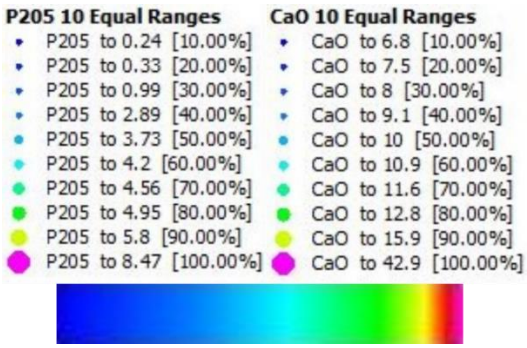
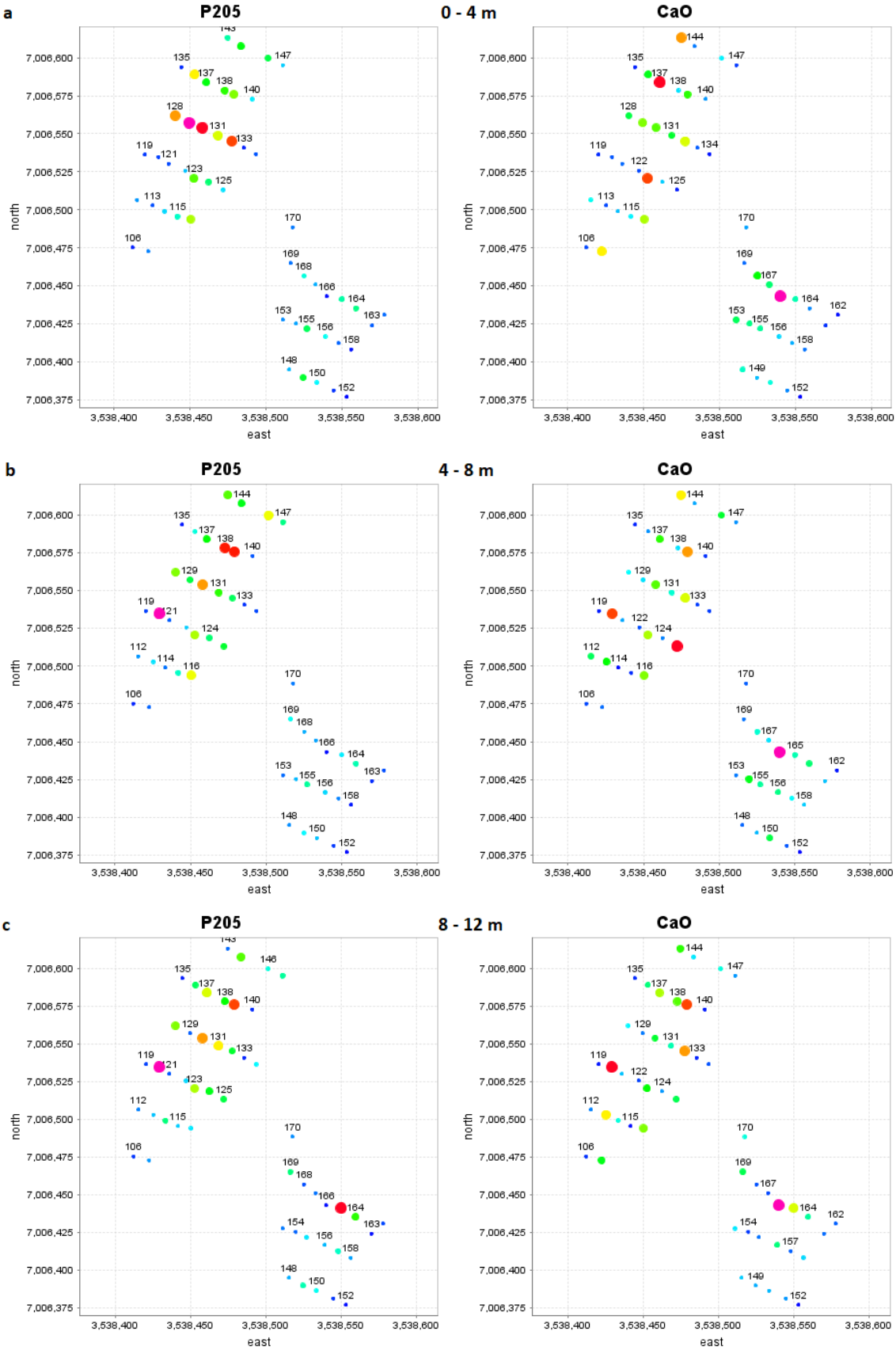


Figure 26: Legend and colour chart of P_2O_5 and CaO contents of sludge samples


a
P205
0 - 4 m
CaO
b
P205
4 - 8 m
CaO
c
P205
8 - 12 m
CaO
north
east
7,006,600
7,006,575
7,006,550
7,006,525
7,006,500
7,006,475
7,006,450
7,006,425
7,006,400
7,006,375
3,538,400
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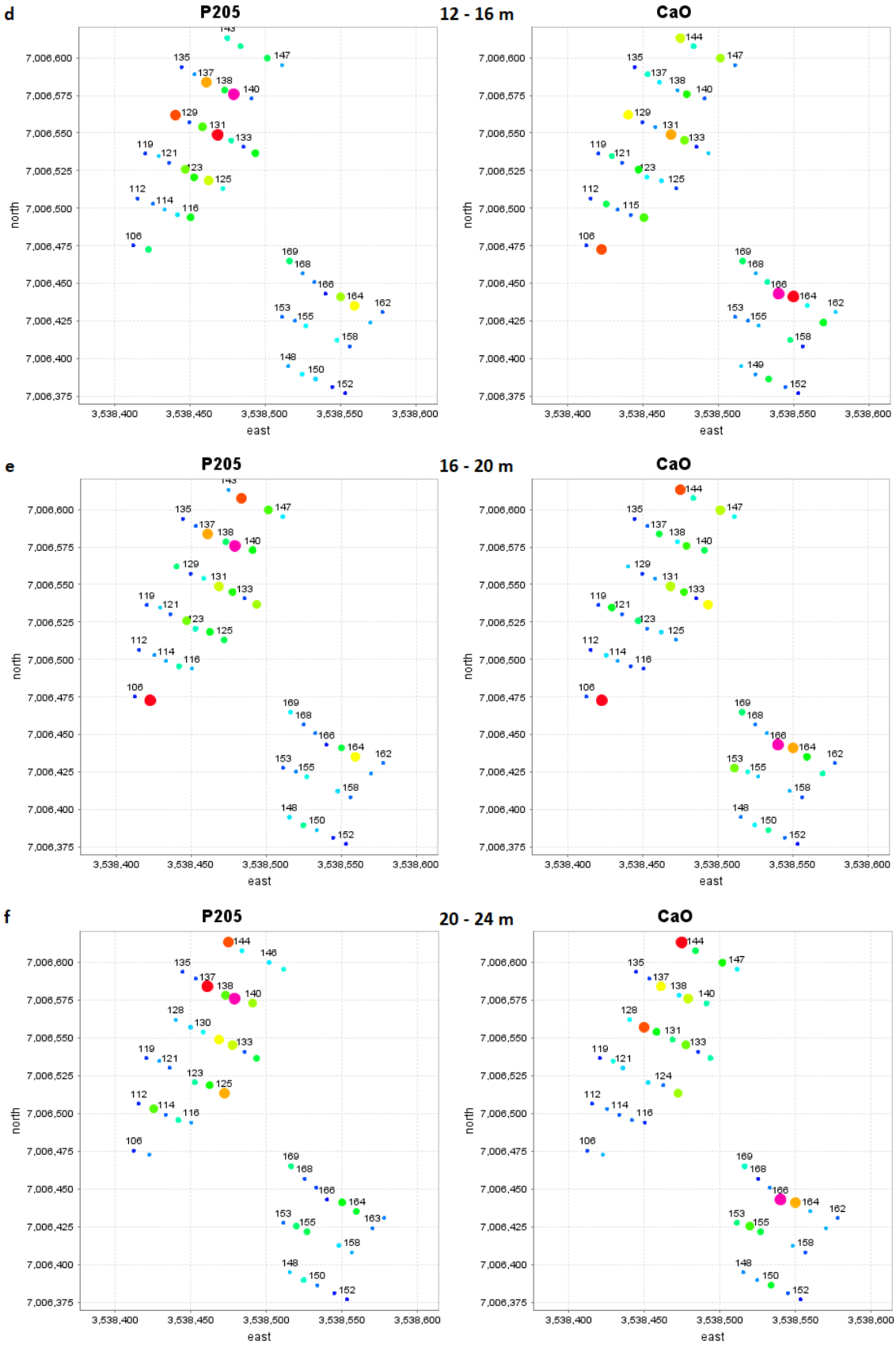
3,538,550
3,538,600



Figures 27a-f: Variable maps of P_2O_5 and CaO contents of sludge samples, depths 0-24 m.

4.3. ICP-MS whole rock analysis

ICP-MS analysis resulted chemical data on element level. Al, Ca, Fe, K, Mg, Na, S and Ti were expressed as percentage and rest of the elements as parts per million (ppm). The results are represented in Table 2. Due to the analysis type, no oxide percentages were received and amount of P exceeded the maximum detection limit, but nevertheless offers information of the rock types containing the most phosphorus. Three samples of glimmerite, all the samples of carbonate-glimmerite and the black dyke sample contained over the upper detection limit of phosphorus. In Figure 28 are the Fe-Ca-Mg contents of the samples plotted on a ternary diagram.

In Table 3 are shown the average carbonatite compositions from Woolley & Kempe (1989) and primitive mantle data from Sun & McDonough (1989) that were used to plot Figure 29 in order to observe the trace-elements and REEs of the Siilinjärvi carbonatite.

Table 2. ICP-MS whole rock analysis data.

sample		P20110 24	P20110 29	P20110 30	P20110 34	P20110 42	P20110 25	P20110 26	P20110 27	P20110 41	P20110 32	P20110 28	P20110 43	P20110 39	P20110 31	P20110 35	P20110 45	P20110 36	P20110 37	P20110 38	P20110 44
rock type		GL	GL	GL	GL (shear)	GL	C-GL	C-GL	C-GL	C-GL	C-GL	CRB	CRB	Black dyke	DB	DB	DB	FEN	FEN	FEN	GN
Al	%	3.06	3.68	3.64	4.42	2.89	3.46	1.07	2.8	3.09	3.67	0.04	0.34	4.17	6.32	7.05	6.76	9.03	6.63	7.22	6.78
Ca	%	5.32	3.57	4.21	5.83	6.99	7.82	23.9	9.75	9.8	5.87	32.9	32.3	6.7	2.53	4.06	5.2	1.35	3.85	2.76	1.04
Fe	%	5.44	7.55	7.57	4.46	5.83	5.23	2.99	5.52	5.19	6.13	0.77	1.41	6.31	10.45	7.14	11.5	1.39	1.36	1.51	1.29
K	%	4.57	7.07	6.86	6.48	4.66	6.07	1.78	4.76	4.97	5.9	0.06	0.55	5.63	6.12	5.71	0.24	3.8	3.66	7.85	0.52
Mg	%	10.4	12.1	12.2	10.5	11.35	10.5	4.91	9.74	10.6	11.15	1.78	2.17	10.05	1.99	3.14	4.39	1.29	0.71	1.56	0.54
Na	%	1.23	0.03	0.03	0.22	1.15	0.04	0.14	0.22	0.29	0.04	0.07	0.07	0.52	2.15	2.13	1.98	4.71	4.77	1.8	5.25
S	%	0.06	0.01	0.04	0.03	0.01	0.01	0.18	<0.01	0.07	0.01	0.04	0.07	0.01	0.42	0.6	0.19	0.01	0.03	0.02	0.01
Ti	%	1.28	0.128	0.122	0.727	0.169	0.117	0.035	0.092	0.233	0.133	<	0.026	0.253	1.17	0.501	0.852	0.035	0.04	0.041	0.204
Ag	ppm	0.03	0.01	<0.01	<0.01	0.01	0.05	0.21	0.36	0.06	0.02	0.05	0.09	0.01	0.5	0.46	0.06	0.07	0.02	<0.01	0.02
As	ppm	<	<	0.2	0.5	<	0.7	0.6	0.6	0.6	0.5	0.6	0.4	<	0.5	0.6	<	0.2	<	0.2	<
Ba	ppm	2490	20	20	1340	190	30	110	30	2700	90	610	430	260	230	5830	30	1240	850	1330	150
Be	ppm	3.22	1.5	1.63	1.74	2.34	0.82	0.36	0.72	1.1	2.24	<	0.47	0.56	1.16	0.36	0.7	0.66	0.94	0.59	0.99
Bi	ppm	0.03	0.03	0.04	<0.01	0.02	0.07	0.04	0.05	0.03	0.06	0.02	0.02	0.04	0.01	0.02	0.01	0.1	0.01	0.01	0.02
Cd	ppm	0.07	0.03	0.04	0.07	0.07	0.05	0.17	0.05	0.1	0.1	0.21	0.22	0.07	0.16	0.06	0.04	0.04	0.05	0.05	<
Ce	ppm	161	89.2	130.5	96.5	137.5	242	441	228	173	145.5	456	490	173.5	67.7	32.8	23.4	41.5	43.3	36.6	143.5
Co	ppm	49.1	31.4	29.7	49	27.5	24.2	23.6	22.7	29.1	29.1	3.7	7.5	28.2	44.2	26.7	57.9	3.8	2.7	3.9	4.4
Cr	ppm	231	7	7	477	7	10	5	5	3	6	2	1	8	10	26	114	4	15	21	13
Cs	ppm	1.63	4.8	4.67	3.82	3.12	4.19	1.28	3.26	3.31	4.77	<	0.4	3.83	1.24	2.62	0.13	1.26	0.07	0.44	0.24
Cu	ppm	2.4	2.4	1.7	0.8	5.1	0.9	28.8	1.8	38.4	2.5	7.7	25.7	2.1	123	118.5	137	4.3	6.4	1.6	2
Ga	ppm	12.7	10.9	10.3	15.3	10.3	9.71	4.75	9.83	11.7	12.3	1.69	3.46	11.7	19.5	14.15	17.2	17.2	16.1	13.8	18.85
Ge	ppm	0.27	0.16	0.19	0.14	0.2	0.39	0.46	0.28	0.23	0.23	0.39	0.45	0.28	0.12	0.11	0.11	0.18	0.18	0.18	0.18
Hf	ppm	5.7	<	0.2	3.5	3.6	<	0.1	0.2	0.5	0.7	<	<	5.3	4.8	1.6	1.9	0.5	0.7	4	5.4
In	ppm	0.057	0.019	0.01	0.021	0.054	0.013	0.031	0.023	0.014	<	0.077	0.044	0.05	0.099	0.052	0.058	0.015	0.026	0.101	0.032
La	ppm	72.7	28.9	42.6	40.1	50.9	78.9	151	74.7	60.3	46.6	171	231	61.8	30.7	13.5	8.9	13.7	15.6	14.4	66.6
Li	ppm	14.3	19.9	19.6	29.9	6.9	20	3	12	7.2	29.3	0.3	0.7	20.5	2.5	11.5	3	15.2	0.8	2.6	2.8
Mn	ppm	674	204	266	657	575	221	756	418	634	257	1110	1280	701	1280	980	2220	143	185	217	143
Mo	ppm	0.15	<	0.06	0.08	0.05	0.05	0.07	<	<	<	0.09	0.07	0.11	1.95	0.13	0.53	0.21	0.28	0.27	0.77
Nb	ppm	78.9	27.7	30.9	3.2	52.9	27.1	13	24.8	25.9	23.5	0.4	10.2	92.7	21.3	5.1	5.9	52.9	1.6	8.2	6.9
Ni	ppm	610	5.6	4.1	670	2.9	5.2	9.8	5.1	4.3	4.2	0.8	0.4	5.7	315	5.7	98	1.4	4	8.2	3.7
P	ppm	1620	>	>	1070	>	>	>	>	>	>	2070	140	>	1340	1070	650	4130	1940	1590	720
Pb	ppm	4.6	1.5	1.6	8.5	2.6	2.5	12.3	3.5	3.8	6.6	14.8	6	1.2	4.4	10.6	1.4	8.6	1.9	1.4	3.1
Rb	ppm	106.5	160	164.5	147.5	191	182.5	75.5	146	153	145.5	2.5	26	182	57.7	93.5	5.1	63.2	27.7	43.8	17.7
Re	ppm	<	<	<	<	<	<	<	<	<	<	<	<	<	0.002	<	0.002	<	<	<	<
Sb	ppm	0.73	0.88	1.37	0.05	0.94	1.66	0.79	1.44	0.97	0.85	0.39	0.63	1.28	0.06	0.05	0.07	<	0.06	<	0.06
Sc	ppm	17.1	1.1	0.5	19.2	15.2	1.1	9.2	3.8	12.2	1.5	18.1	5.5	22.6	29.2	27.7	40.4	1	1.1	28.7	2.4
Se	ppm	<	<	<	1	<	<	1	1	<	<	1	1	<	1	1	1	1	<	<	<
Sn	ppm	2.1	0.4	0.6	0.4	1.2	0.3	<	0.2	0.5	0.4	<	0.2	2	1.6	0.8	1.2	1.2	1.7	2.5	1.8
Sr	ppm	1160	528	696	1990	955	1570	4240	1770	1770	964	5860	6210	955	235	1070	330	392	901	381	275
Ta	ppm	5.48	2.16	2.53	0.19	2.27	1.9	0.59	1.85	1.48	1.7	<	0.25	4.8	1.12	0.26	0.38	2.67	0.12	0.38	0.21
Te	ppm	<	<	<	<	<	0.06	<	0.2	<	<	0.06	0.07	<	<	<	<	<	<	<	<
Th	ppm	8.75	0.73	1.45	2.73	1.78	1.17	1.55	0.89	1.02	1.35	0.15	0.68	1.48	3.76	1.35	2.35	0.68	0.28	0.5	28.9
Tl	ppm	0.25	0.43	0.49	0.56	0.41	0.37	0.12	0.3	0.32	0.59	<	0.04	0.63	0.2	0.36	<	0.16	0.06	0.19	0.07
U	ppm	0.7	0.2	0.3	0.6	0.3	0.2	0.2	0.3	0.1	0.3	<	<	0.3	0.8	0.5	0.5	0.1	<	0.1	1
V	ppm	83	56	56	28	86	32	22	41	82	63	1	22	122	322	186	314	40	31	118	24
W	ppm	0.1	<	<	0.2	0.1	<	<	<	0.1	<	0.1	0.1	0.2	0.1	<	0.4	0.1	0.1	0.1	0.2
Y	ppm	13.8	5.1	7.5	11	9.5	14.8	32.8	15.8	14.5	9.2	38.8	46.5	10.5	29.4	15.9	29	3	3.6	2.8	9.5
Zn	ppm	71	48	52	70	65	34	14	34	42	88	2	9	115	126	82	102	26	7	16	15
Zr	ppm	198.5	1	10.2	108.5	103.5	1.3	2.5	9.5	12.5	26.8	<	1.2	181.5	181	62.5	68.9	35.2	50.7	152.5	192

ICP-MS detection limits: (%) Al, Ca, Fe, K, Mg, Na, S, Ti (0,01%), (ppm) Ba and P = 10; Mn = 5; Zn = 2; Cr, Se and V = 1; La, Pb and Zr = 0,5; As, Cu, Li, Ni, Sn, Sr = 0,2; Co, Hf, Nb, Rb, Sc, U, W and Y = 0,1; Be, Cs, Ga, Ge, Mo, Sb, Ta and Te = 0,05; Cd and Tl = 0,02; Ag, Bi and Ce = 0,01; In = 0,005; Re = 0,002. < = below detection limit, > = above detection limit

abbreviations: GL=glimmerite, C-GL=carbonate-glimmerite, CARB=carbonatite, DB=diabase, FEN=fenite, GN=gneiss

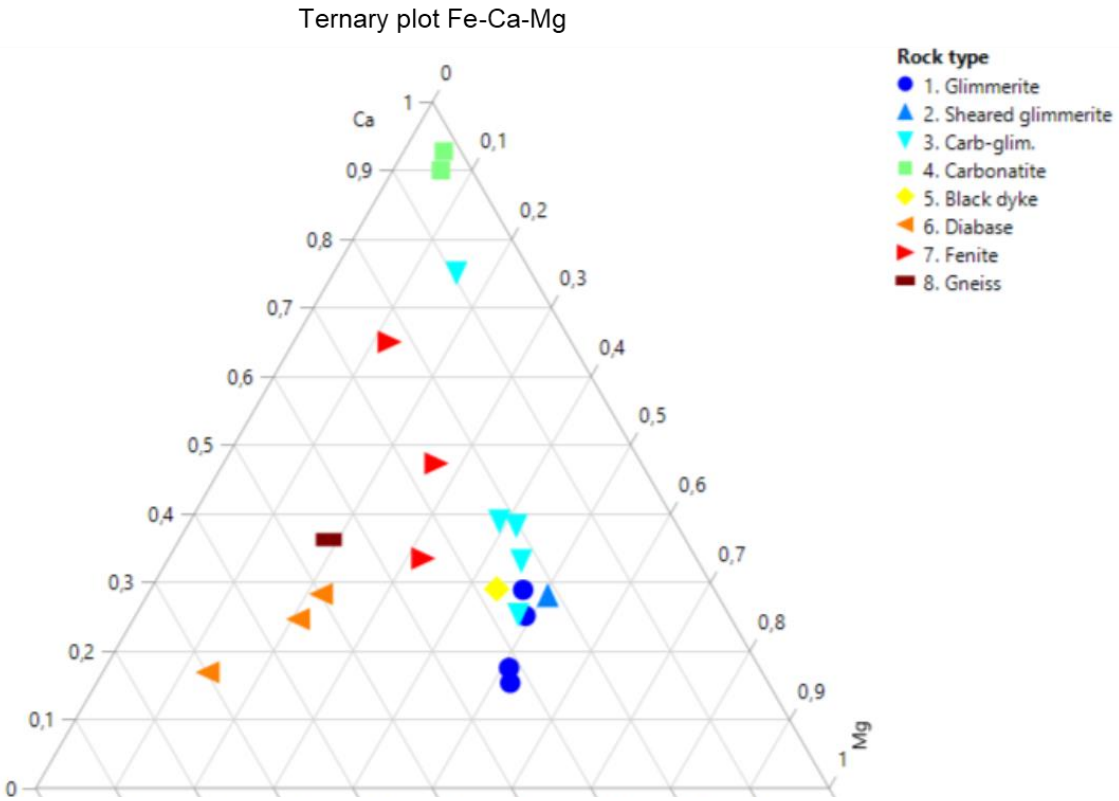


Figure 28. Ternary diagram Fe-Ca-Mg of the analysed samples from Table 2.

Table 3. Element concentrations (ppm) in samples from Saarinen, average carbonatite (Woolley & Kempe, 1989) and primitive mantle (Sun & McDonough, 1989).

	Glimmerite	Carbonate-glimmerite	Carbonatite	Black dyke	Diabase	Fenite	Gneiss	Average carbonatite	Primitive mantle
	n=5	n=5	n=2	n=1	n=3	n=3	n=1		
Cs									0.008
Tl									0.005
Rb	153.9	140.5	14.25	182.0	52.1	44.9	17.7		0.635
Ba	812.0	592.0	520.0	260.0	2030.0	1140.0	150.0	3045.0	6.989
W	0,12*	0.1	0.1	0.2	0.25	0.1	0.2		0.02
Th	3.088	1.196	0.415	1.48	2.487	0.487	28.9		0.085
U	0.42	0.22	0,1*	0.3	0.6	0.1	1.0		0.021
Nb	38.72	22.86	5.3	92.7	10.767	20.9	6.9	1204.0	0.713
Ta	2.526	1.504	0.25	4.8	0.587	1.057	0.21		0.041
K	5.928	4.696	0.305	5.63	4.023	5.103	0.52		250.0
La	47.04	82.3	201.0	61.8	17.7	14.567	66.6	608.0	0.687
Ce	122.94	245.9	473.0	173.5	41.3	40.467	143.5	1687.0	1.775
Pb	3.76	5.74	10.4	1.2	5.467	3.967	3.1		0.071
Pr								219.0	0.276
Mo	0,078*	0.06	0.08	0.11	0.87	0.253	0.77		0.063
Sr	1065.8	2062.8	6035.0	955.0	545.0	558.0	275.0	7272.0	21.1
P	6538^	10000^	1105.0	10000^	1020.0	2553.333	720.0		95.0
Nd								883.0	1.354
F									26.0
Sm								130.0	0.444
Zr	84.34	10.52	1.2	181.5	104.133	79.467	192.0	189.0	11.2
Hf	2,62*	0.375	0,1*	5.3	2.767	1.733	5.4		0.309
Eu								39.0	0.168
Sn	0.94	0.35	0.2	2.0	1.2	1.8	1.8		0.17
Sb	0.794	1.142	0.51	1.28	0.06	0.06	0.06		0.005
Ti	0.485	0.122	0.026	0.253	0.841	0.039	0.204		1300.0
Gd								105.0	0.596
Tb								9.0	0.108
Dy								34.0	0.737
Li	18.12	14.3	0.5	20.5	5.667	6.2	2.8		1.6
Y	9.38	17.42	42.65	10.5	24.767	3.133	9.5	119.0	4.55
Ho								6.0	0.164
Er								4.0	0.48
Tm									0.074
Yb								5.0	0.493
Lu								0.7	0.074

*= one or more analysis result below detection limit, result changed into min. detection limit

^= one or more analysis results above detection limit, result changed into max. detection limit

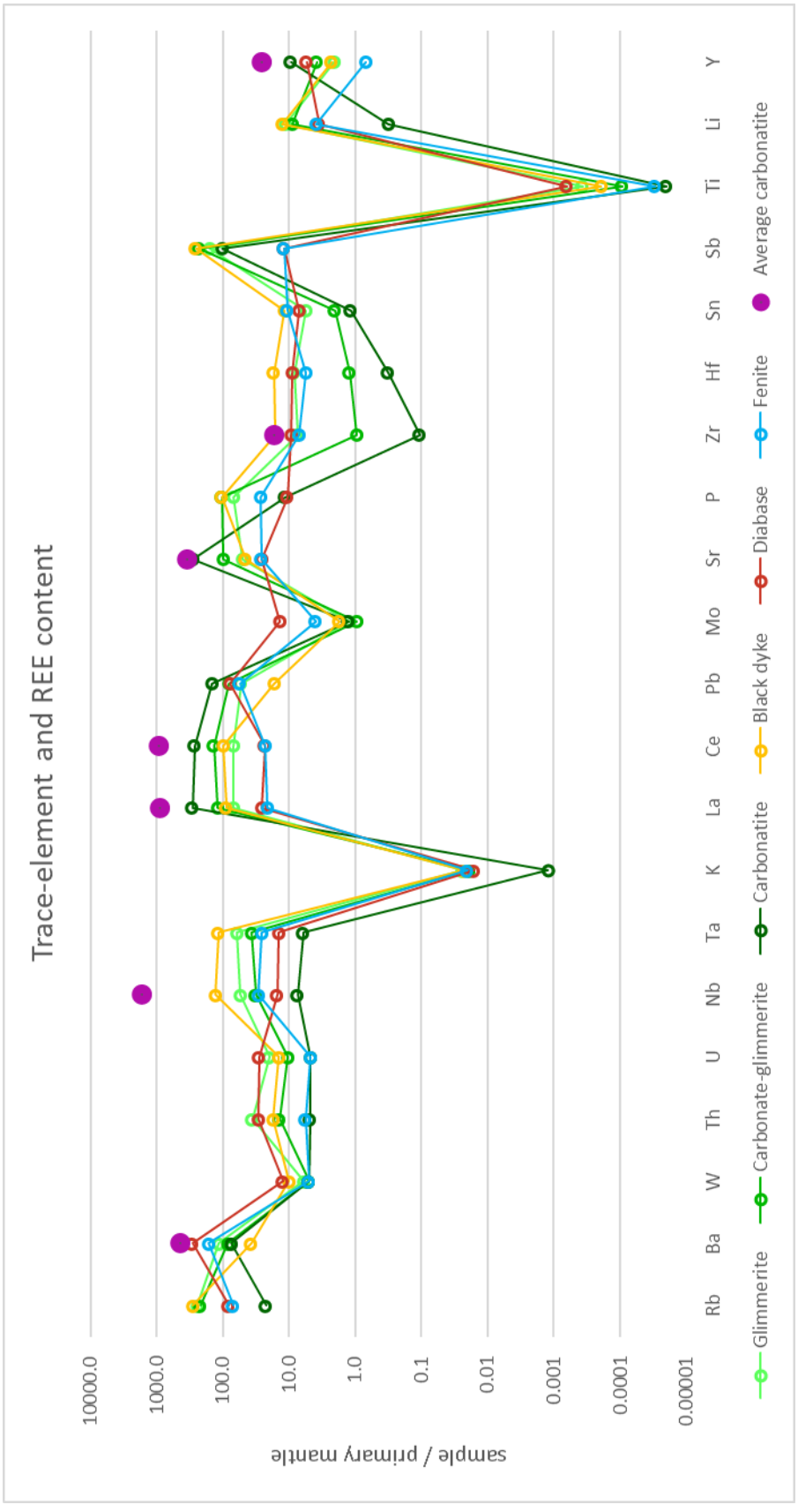


Figure 29. Primitive mantle normalized trace-element data of the Saarinen glimmerite-carbonatite rocks. Average carbonatite data from Woolley and Kempe (1989) and primary mantle data from Sun and McDonough (1989).

5. DISCUSSION

5.1. Carbonatites of the Earth

Carbonatites are igneous carbonate-bearing rocks. The definition of carbonatites has changed in the last decades as understanding of their magmatic origin has grown. Before the main definition of carbonatites based on their carbonate mineral amount but Mitchell (2005) concluded that more than their carbonate mineral amount, the classification of carbonatites is based on the way how carbonatite-forming magma results into several different carbonate-bearing rocks. The carbonate content of these different rocks varies greatly and is not in the key role when determining a carbonatite. For guidance however, Mitchell (2005) gave an arbitrary value of 30 vol.% of carbonate minerals in carbonatite.

Carbonatites form only a minute part of Earth's magmatism but provide an important insight into the planet's magmatic past. Carbonatite magmatism has started in the Archaean and the activity has increased during time. The Siilinjärvi glimmerite-carbonatite complex represents one of the oldest carbonatite intrusions. Most of the carbonatites with economical value are younger. Carbonatites are usually associated with continental rifting but are also common in orogenic belts and occur worldwide, but the majority of the carbonatite locations are in Africa, Fennoscandia, Mongolia, China, Australia, South America and India. Most of the carbonatites are associated with alkaline rocks and fenitization around them is commonly present. Besides phosphorus, carbonatites host rare metals and REE, making them economically interesting and significant (Randive and Meshram, 2020).

Carbonatite magmas have a complex origin and they often seem to be the product of a multi-source origin. Andersen (1989) notes that it is known that carbonatites can originate from liquid immiscibility of carbonatite and silicate melts, fractional crystallization and exchanges of components between magmas and fluid phases. This is verified by Bell et al. (1999) and in their research was also noted that isotope data of Nd, Pb and Sr from western and northeastern Indian Cretaceous carbonatites give evidence for carbonatite magmatism to arise from plume activity and that the parent melt of carbonatites can be

produced from primary mantle melting. Based on studies of isotopes (Sr-Nd-Pb), noble gases, composition and experimental phase equilibria, it is proven that carbonatites originate from mantle melt with no significant signs of crustal contamination (Jones et a. 2013).

Some research has concluded that strongly alkaline carbonatite magma can be the parental melt for the alkali-poor carbonatites due to the loss of alkalis (ia. Le Bas 1987). The initial high alkali content also gives rise to fenitization of the poor alkali wall rocks, also offering evidence of high alkali contents of the initial magma (Woolley 1982, Andersen 1989), resulting a carbonatite rock poor of alkalis.

5.2. Mapping

Mapping of Saarinen was restricted in the area where soil was removed. The area has been divided into western and eastern part due to a stream that run in the middle of the area and the soil could not be removed near the stream. A more detailed mapping was performed in the middle of the western part where the rock surface was washed with high pressure water to obtain more detailed information of the rock type variation within the glimmerite-carbonatite.

There were some troubles with the Leica GNS mapping. Sometimes the GPS-signal was difficult to find and the strength and accuracy of the signal varied during mapping. This may result as errors in location data, the maximum error being in meter scale. Some GPS files lacked information of elevation of mapped points. At one time the Leica recorder lost a file, which was later successfully retrieved by Leica.

5.3. Geochemical and trace element composition of the complex

All the data from the ICP-MS analyses are represented in Table 2. Table 3 contains the data of the rock types of the with the complex (glimmerite-carbonatites and fenite), dyke rocks (diabase and black dyke), basement rock (gneiss) with data of average carbonatite

(Woolley and Kempe 1989) and primitive mantle data (Sun and McDonough 1989). In Figure 28 all the analysed samples are plotted on a ternary Fe-Ca-Mg diagram.

In Figure 29 the trace-element data and average carbonatite data is plotted against primitive mantle normalized data. The one analysed gneiss sample is shown on Table 3 for reference of the country rock but is excluded from the diagram (Figure 29) because it was not studied any further. Fenite is taken into comparison due to a metasomatic relationship to the glimmerite-carbonatite, and black dyke and diabase in order to observe the black dyke's geochemistry and possible relation to other rock types.

The data from Table 2 supports my observations and classification of glimmerite-carbonatite series rocks into their subcategories when taking the Ca content of the rocks into account. Sample P2011 026 contains more Ca than the other rocks in the carbonate-glimmerite category but still less than the carbonatite samples, this is visible also from ternary diagram (Figure 28), where this sample is shown as a light blue triangle at ~0.75 Ca line. It also has less K, Mg and Al, which implies less phlogopite than other carbonate-glimmerites. Also several other trace elements fall in between these two higher carbonate content categories (higher levels of Ba, Cd, Ce, Ge, La, Pb, Sr and Y and lower levels of Cs, Ga, Li, Nb, Rb, Ta, V, Zn than other same category rocks). This rock sample could be classified into the silico-carbonatite subcategory by Härmälä (1981), while rest of the samples of carbonate-glimmerite fall within the similarly named subcategory.

From Table 2 can be seen that the highest phosphorus, hence apatite, concentration is in the moderate carbonate containing rocktype, carbonate-glimmerite, in fact all the samples in this category contained phosphorus over the maximum detection limit. In addition, the black dyke sample was rich in phosphorus, but as there was only one analysed sample, it is not known whether the black dyke as a whole is rich in apatite or whether the collected sample happened to contain apatite. Glimmerite contains a significant amount of phosphorus but carbonatites remarkably less, even fenites contain more . Hence it is notable that the highest apatite content is associated with the rocks containing moderate amount of carbonates.

From Figure 29 can be seen that Siilinjärvi carbonatite is depleted in three REEs (La, Ce, Y) compared to the contents in average carbonatite. Monazite is a phosphate mineral and the main mineral containing La and Ce and is an abundant and typically one of the most important REE minerals occurring in carbonatites. Monazite occurs as primary minerals in carbonatites but especially associated as a secondary mineral associated with apatite (Chen et al. 2017). Carbonate-glimmerites contain the highest amount of P, hence phosphorus in apatite, but La and Ce values correlate better with Ca than P, which suggests that monazite at Siilinjärvi is mainly associated with carbonates (calcite). Thair Al Ani (2013) found monazite inclusions within calcite in addition to apatite.

Carbonatites and associated alkaline-silicate rocks are the most important source for Nb, the most important Nb-bearing mineral being pyrochlore. Nb is used in e.g. in steel production and superconducting magnets. Nb deposits are found in primary carbonatites as a result of early crystallisation of Nb-bearing minerals but most important deposits are those of supergene laterites formed by near surface weathering of carbonatites (Mitchell 2015). The Nb content of Siilinjärvi carbonatite is remarkably less than in average carbonatite (Table 3 and Figure 29).

Black dyke has many similarities with the glimmerite-carbonatite, most notably a high P content. If compared to both the glimmerite-carbonatite series rocks and diabase, it resembles the first in most of the elements, most notably the REEs Ce, La, Y and many trace elements and all the main group elements. It differs from the ore rocks most notably in the higher Nb and Ta content, which occurs in association with pyrochlore (Wenk and Bulakh 2004). The black dyke resembles lamprophyre dykes.

5.4. Glimmerite-carbonatite series rocks

The visible difference between the two major rock types of the glimmerite-carbonatite series, the less carbonate containing rocks and carbonatite proper, is most likely caused by separate stages of intrusions. First the ultramafic melt intruded into a major fault or weakness zone within the basement rocks and caused fenitization of the wall rocks. The carbonatite proper intruded at a later stage in the middle of the glimmerite-carbonatite

rocks. This interpretation of sequence is supported by Härmälä (1981). The reason why some of the carbonatites have very sharp contact and others slightly gradual may be due to a long time span in setting of the carbonatite proper – the ones with sharp contacts were possibly even later intrusion into a more cooled and rigid glimmeritic rocks while the carbonatite “dykes” with more vague contacts were intruded into a still warm and ductile glimmerites.

This is evident from the nature of the contact between carbonatite to the other members of the glimmerite-carbonatite intrusion, as the contact is distinctive but not always completely sharp, occasionally gradual over centimetre scale. Carbonatite typically occurs in the middle of the complex, as is evident from the map (Figure 6), which also supports this theory as the glimmeritic rocks at the edges, adjacent to cool country rocks, would have already been more cooled and the warmer central part giving way for the carbonatitic magma to intrude. Evidence for slow cooling and ductile magma also arises from typical oriented appearance of the rocks and xenoliths that have often adapted an elongated shape – parts of country rock have been grabbed by the intruding magma and been partially melted, although fenitization itself is metasomatic alteration. In addition, phenocrysts of glimmerite and apatite are evidence for slow cooling. The overall volume of the most carbonate rich variety is very small compared to the glimmeritic varieties. The difference of composition of these two phases is most likely due to either magma evolution or separation of the melt facies. Later the complex and adjacent country rocks were cut by multiple sets of dykes, among others the diabases and black dyke discussed in this study.

Subcategories glimmerite, carbonate glimmerite and silico carbonatite are more of a flowing sequence of rocks of same type and in the field have indistinctive rocktype boundaries. These subcategories were formed originally by Härmälä (1981) to aid mapping and to categorize the rocks. Overall, the rocktypes could also be simplified into glimmerite and carbonatite to make a distinction between the two main types within the series.

Glimmerites always show some orientation of crystals, but this is most likely an original feature from the emplacement and not due to a later shearing event.

Phlogopite, the main constituent mineral in the complex, occurs in many textures. Being a very distinctive mineral due to its softness with the platy cleavage, at field it is easily recognizable and offers information of orientation of the rocks and localised shearing occasionally observed. Puustinen (1973) has studied the phlogopite in more details, resulting that some of the phlogopite is tetraferriphlogopite, in which ferric iron $Fe^{3}+$ has replaced Al^{3+}. The variation in the Mg – Fe – Al content is responsible for the variation in colour of phlogopite. Phlogopite and richterite amphibole typically coexist in the rocks.

Apatite is especially common accessory mineral in magmatic rocks and is found as a minor phase in most igneous rock types, in metamorphic rocks of all grades and is virtually always present in clastic sedimentary rocks (Chew and Spikings 2015). Aside from rocks, apatite is the main constituent of bones and teeth and it has many applications in e.g. medical technology.

The name “apatite” is used as a reference to the apatite supergroup comprising of over 40 mineral species. Although chemically diverse, the apatite supergroup minerals share a common atomic arrangement. The most common minerals are calcium phosphate apatites belonging to the “apatite subgroup”, normally referred simply as “apatite”. The different phosphate apatites are either hydroxylapatite (accommodating OH), chlorapatite (Cl) and fluorapatite (F) and their formula is $Ca_5(PO_4)_3(OH, Cl, F)$. The apatite in the Siilinjärvi carbonatite belongs to the latter (Hughes and Rakovan 2015). Apatite in the glimmerite-carbonatite occurs as both mineral integrates of anhedral crystals, similarly to calcite and in addition as separate, euhedral grains, which are usually smaller in size. It is likely that apatite has crystallised in two different stages, the euhedral grains originating from an earlier crystallization phase at a deeper level.

Puustinen (1971) noted that he did not find any signs of alteration in the amphibole, but at least in the samples from Saarinen in this study, signs of phlogopite-richterite alteration reactions are present (Figure 14). Signs of alteration are visible even in hand specimens,

where in places the richterite crystals are surrounded by phlogopite with an unclear boundary and occasionally the richterites are surrounded by radiating phlogopite. Phlogopite was also found as lamellae in the cleavage planes of richterite, as a proof of alteration between the two.

The amphibole content of the rocks is occasionally very high, e.g. in samples P2011 026 and 042, thus the rock could be called amphibole-glimmerite.

Zircon occurs as an accessory mineral in the different rock types of the complex and can be found in both glimmerite-carbonatite series rocks and in fenite. Sometimes zircons form large eu- to subhedral crystals. Poutiainen (1995) has studied the fluid inclusions on zircon and apatite. The results showed two different fluid phases, named type 1 and type 2, which are both found in zircons.

Carbonatites are easily disturbed by post-magmatic events and thus seldomly carry an uninterrupted evidence of its magmatic past. Zircon and apatite are early formed and are an important source for the studies of the history of carbonatites, as they carry evidence from the pre-emplacement conditions in the fluid inclusions (Poutiainen 1995). The U-Pb zircon age of the formation is ca. 2,6 Ga (Geological survey 1978).

5.5. Country rocks – basement gneiss and fenite

The contact between the glimmerite-carbonatite complex rocks and gneiss was recorded in the southeastern and eastern parts of the mapped area. The gneiss appears stripy or banded and is reddish in colour. Gneiss was not studied in any further detail in this study, only the accurate locations of the contacts that were visible were under interest.

Fenite is a term describing a metasomatically altered rock at a carbonatite intrusion. The term “fenitization” describing the metasomatic process refers to alkali metasomatism, which is one of the four different types of metasomatism described by Andersen (1989) in the type locality Fen, Norway. The other types of metasomatic processes described by Andersen (1989) at the Fen complex are magnesium metasomatism (phlogopite replaces

feldspar in fenite), ferromagnesian metasomatism (dyke facies ferrocarbonatite has caused increase in ferromagnesian components in calcite of the wall rock carbonatite) and pseudomorph replacement of phlogopite by chlorite.

In the Siilinjärvi glimmerite-carbonatite complex fenite is met adjacent to the glimmerite-carbonatite series rocks so it would have been directly metasomatized by the leaching alkalis. It is also met as xenoliths in the glimmerite-carbonatite rocks, especially in the outer parts. Most of the xenoliths are small and below a mappable scale, but many major xenoliths have been recorded in the map (Figure 6). The fenite xenoliths are brecciated rocks detached from the country rocks during the intrusion of the glimmerite-carbonatite. These blocks have then been fenitizised. The xenoliths are often elongated or drop shaped because they have partially melted while carried within the intruding magma. Puustinen (1971) concluded that the rock type now called fenite, would have been a later intrusive syenite between the carbonatite complex and basement gneiss, but the xenoliths are a strong evidence for the fenitization adjacent country rocks.

The appearance of the fenite resembles gneiss which substantiates metasomatism. The bluish-green tint of the rock arises from the amphiboles and pyroxenes, as well as mainly grey feldspars.

Most of the contacts observed between the fenite and gneiss were gradual, supporting the fenitization of country rocks. In few places the contact occurred over or was disturbed by a fracture zone.

5.6. Dyke rocks

The diabase dykes at Saarinen are north-south oriented along the direction of the complex. In the larger scale the diabases within and around the glimmerite-carbonatite complex are northwest-southeast trending. The rocks of the glimmerite-carbonatite complex show lineation parallel to the north-south overall orientation of the intrusion. The minerals show occasionally strong lineation and in addition, the carbonatites of a probable later pulse of carbonatitic magma in the middle of the complex are oriented in similarly. This

is likely due to the soft and permeable nature of the glimmerites, which might have given way for the diabase dykes to intrude the complex along the planar weaknesses within the glimmerite-carbonatites series rocks. Or the diabases may be part of a smaller event of dyke intrusion independent of the larger scale dyke set in the area.

Two or more generations of diabase dykes were found, based on the differences in mineralogy. Because some of the diabase dykes were magnetic and some not, it can be assumed that they belong to at least two separate intrusive phases. The grain size and overall texture and mineralogy of the diabases also vary from each other, which may be original features or arise from later metamorphism.

Härmälä (1981) studied the rocks in the main Särkijärvi open pit and noted that besides "normal" diabases, another type of dykes is present, he called them "dark dyke". He makes a short account of the rock type in his master's thesis and concludes that these would be altered diabase dykes because he found similar material at the edges of diabase dykes. It is not known whether Härmälä's dark dykes are the same rock as the "black dyke" I discovered. At Saarinen I did not encounter alteration in diabases that would have resembled the black dyke, also diabases were very distinctive with sharp contacts and they occurred in a straight manner and could be followed in longer distances than the black dyke. The black dyke had more undefined shape and its overall orientation was not easily observable.

Taking into consideration the similar mineralogical composition, texture and chemical similarity of the black dyke and glimmerite, with the exception of phlogopite being replaced by another mica in the black dyke, I presume this black dyke could be originating from the same magma source, being either a later pulse of the original magma or displaying an evolution of the magma source and being a residue magma from the magma chamber.

5.7. Chemical variability of sludge samples

The sludge samples are a very rough estimation of rock type. Only the rock type on the surface could be observed with certainty. Overall, the analysis results show that all the rock type observations during the sludge sampling were well estimated (observed rock types are listed in Appendix 3 and Appendix 4). Samples were taken of ground rock in four-meter vertical sequence and any small scale, less than one-meter rock units (e.g. xenoliths) could not be observed during sample collection, and those may change the analysis results. If lithology very obviously changed from one to another during the 4 m interval, the change was recorded in the field notes.

The Figures 27a-f show P_2O_5 and CaO concentrations of each 4 metre sample intervals. P_2O_5 and CaO were chosen for the diagrams to represent the ore rocks. From the diagrams can be seen that different rock types are not often continuous over long depths; the plotted data shows that the samples from drill holes are very variable across the depth.

5.8. Evaluation of data collection and results

In the sampling process there is a possible error in contamination of the samples. Due to the nature of the glimmerite rocks, micaceous dust covers rocks all over and might have ended up contaminating samples. Sludge sampling by its nature is very inaccurate and due to the sample frequency and type of sampling, in which several metres of ground rock is being mixed, the samples are very rough estimations to start with, hence any contamination would not affect the analysis data significantly. Most of the sludge sample drillings reached full 24 metres but occasionally water was encountered at higher level and drilling had to be discontinued at those locations. These locations are easily observed from Appendix 1 and Appendix 2, as the depths of the samples are recorded in the table.

Due to the small-scale variation of carbonate content of the rocks, for the purposes of sample collection, I simplified the categories and combined the two middle categories and called them jointly carbonate-glimmerite. The different types of the glimmerite-carbonatite series rocks were determined by visual observation, basically how “light” the

rock looked like. Based on whole rock data, categorising the rock samples at collection was successful and the naming the rock types was consistent at field. Due to the large quantity of sludge samples, the data of geochemical variation would be best presented in 3D variable maps. Due some conflicts with timing with the high pressure washing of the rock surface at Saarinen, some areas that were later blasted could have benefited from more detailed sampling.

6. CONCLUSIONS

This study and the mapping data of the exposed rock surface at Saarinen support the theory of two phases of magma pulse of the complex. Firstly, the carbonate poor and apatite rich glimmeritic parts of the glimmerite-carbonatite complex were being intruded. In the latter part the carbonate rich and apatite poor carbonatite proper was intruded into the earlier glimmeritic parts. The glimmeritic magma has been responsible for the fenitization of the adjacent country rocks. Whole rock geochemical data from Saarinen is analogical to the known fact that the apatite is concentrated in the more glimmeritic parts of the complex and carbonatite proper is apatite poor compared to the other, earlier members of the glimmerite-carbonatite complex rocks.

Further studies of the dyke phases would be beneficial in understanding the whole complex, especially the “black dyke”, even though being only a minor phase. If it was originated from the same source as the rocks of the main glimmerite-carbonatite intrusion, further study of the black dyke could offer more in-depth knowledge of the complex and the original magma and the evolution of it.

The terminology for carbonatites in this study followed the old definition by Streckeisen (1980). Härmälä (1981) based his classification of the rocktypes of this complex on the definition of a carbonatite used at the time. For this reason, all the rock names used at the Siilinjärvi mine followed that terminology and classifications. Carbonatites have been under a lot of research in the past decades and understanding the nature and origin of this rock series has grown. In the new definition by Mitchell (2005) it is acknowledged that

the definition of carbonatites, a wide variety of igneous carbonate-bearing rocktypes, is important to be based on their magmatic origin and associated rocks of the complex or series. Therefore, in this study the complex is called more precisely glimmerite-carbonatite, to emphasis the rocks (glimmerites) associated with the carbonatite. It would be beneficial to classify the members of the Siilinjärvi glimmerite-carbonatite complex even more precisely to follow the modern classification of carbonatites for the purposes of future research.

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9. APPENDICES

Appendix 1.

Sludge sample locations and analysis results

Saarinen west

	depth		location											
sample code	from (m)	to (m)	x	y	z	P205	CO2	K20	MgO	CaO	Na2O	SiO2	Fe2O3	Al2O3
S2011106	0	4	3538412,214	7006475,246	127,017	0,24	11,6	3,9	23,3	7,5	0,33	36	8,7	4,1
	4	8				0,22	9,2	2,9	24,1	7,2	0,28	35	8,3	3,4
	8	12				0,27	10,4	3,7	24,7	7	0,35	35	9	3,7
	12	16				0,26	10,7	2,9	24,8	6,7	0,1	33	9,3	3
	16	20				0,2	10,7	3	24,8	6,9	0,1	34	8,9	3,1
	20	24				0,22	10,8	3,9	23,7	7,3	0,1	34	7,9	4,1
S2011107	0	4	3538422,516	7006472,767	126,394	2,43	14	5,6	14,8	18,6	0,71	28	6,6	6,2
	4	8				1,28	5	4,2	6,3	8,7	5	49	6,6	11
	8	12				2,11	7,4	6,2	16,9	13,7	0,69	35	7,1	6,6
	12	16				4,69	17,2	3,9	13,5	23,7	0,34	22	6	4
	16	20				5,76	16,1	3,7	12,8	24,4	0,31	21	5,8	3,8
	20	24				2,57	3,7	5,7	18,5	9,7	0,63	37	8,2	5,9
S2011112	0	4	3538415,327	7006506,344	129,407	2,89	4,9	6,5	17,7	10,7	0,87	36	7,7	7,6
	4	8				3,1	5,5	6,6	17,5	11,7	0,55	35	7,8	7,1
	8	12				1,99	4,6	6,4	19,7	9	0,44	36	8	6,8
	12	16				0,44	6,8	5,1	22,9	6,9	0,28	37	7,8	4,9
	16	20				0,34	8,7	4,5	24,6	6,1	0,1	36	8	4,2
	20	24				0,31	8,8	3,7	26,2	6	0,1	35	8,4	3,6
S2011113	0	4	3538425,413	7006503,047	128,016	0,47	4,4	6,1	20	7,5	1,7	40	8,3	6
	4	8				3,78	6,7	6,5	15,8	12,7	1,1	32	6,8	7,8
	8	12				3,38	10,7	5,9	15,6	17,2	0,77	29	6,7	6
	12	16				1,92	7,6	6,6	17,4	12	0,55	32	7,1	6,8
	16	20				2,05	6,4	7,2	18,7	10	0,4	32	8,3	7,2
	20	24				4,84	2,1	7,3	18,7	8,5	0,41	33	8	7,3
S2011114	0	4	3538433,359	7006499,048	126,329	3,73	5,1	7,5	13	9,6	1,7	37	6,1	12,2
	4	8				2,06	1,3	7,1	7,1	4,2	3,8	49	3,8	17,3
	8	12				4,39	4,2	7	7,4	10,6	2,7	42	4,3	13,8
	12	16				3,34	2,9	8,6	7,8	8,5	2,5	47	4,7	16,2
	16	20				2,21	3,7	7,2	14,6	9,1	1,6	41	6,9	9,6
	20	24				1,11	4,1	6,8	17,5	7,7	1,5	40	7,8	7,8
S2011115	0	4	3538441,792	7006495,55	124,733	4,22	7	7,5	19,3	10,6	0,15	31	8,4	7,3
	4	8				4,32	2	8,5	21,4	6,9	0,14	34	9	7,9
	8	12				3,53	1,3	8,7	22,1	5,4	0,1	36	9,4	7,7
	12	16				4,11	3,9	7,7	20,4	7,9	0,19	32	9,1	6,9
	16	20				4,37	1,8	8	21,1	6,8	0,16	34	9,5	7
	20	24				4,34	3,9	7,7	19,3	8,4	0,18	32	9,1	7,3
S2011116	0	4	3538450,405	7006493,856	124,919	5,69	8,6	6,6	17,4	15,2	0,24	28	7,8	6,5
	4	8				6,09	6,1	7,2	17,6	13,6	0,46	31	7,8	7,2
	8	12				3,84	11,4	6,6	17	16	0,31	28	7,7	6,3
	12	16				4,9	8,3	6,7	18,5	14,1	0,42	30	8,6	6,6
	16	20				2,46	3,2	10	9,5	6,2	1	45	5,1	12,6
	20	24				2,72	2	10,4	11,3	5,8	0,72	44	6	12,3
S2011119	0	4	3538420,496	7006536,451	129,245	0,3	9,8	3	26,1	6,9	0,2	35	8,9	3
	4	8				0,28	8,9	2,4	28,9	5,6	0,1	35	9,2	2,3
	8	12				0,29	13	2,6	25,2	7,9	0,1	34	9,3	2,5
	12	16				0,34	10,9	2,7	25,8	7,1	0,1	33	8,9	2,6
	16	20				0,36	13,9	2,3	25,9	6,8	0,1	31	9,1	2,3
	20	24				0,33	12,3	2,1	28,4	5,1	0,1	32	9,3	2

S2011120	0	4	3538429,346	7006534,683	130,699	0,32	4,4	7,2	19,1	7,6	0,89	37	6,8	7,5
	4	8				9,34	7,4	5,9	14,6	21	0,37	27	6,7	5,6
	8	12				3,46	13,6	6,2	16,7	17,4	0,1	25	6	6
	12	16				3,73	5,7	7,6	18,2	11	0,69	34	8	8,1
	16	20				3,52	5,4	7,1	16,4	12,1	1,5	38	8,3	8,6
	20	24				2,82	5,9	6,3	14,9	11,8	1,9	37	8,1	8,3
S2011121	0	4	3538435,941	7006530,23	130,097	0,33	4,1	6,4	19,1	8	1,5	39	7,4	6,4
	4	8				1,05	5,4	6,3	17,9	9,6	1,5	37	7,7	6,4
	8	12				0,8	4,6	6,9	17,6	8,5	1,3	38	6,9	7,4
	12	16				0,65	4,3	6,5	19,4	7,6	1,4	39	7,4	6,6
	16	20				0,71	4,4	7,1	18,9	7,7	1,1	38	7,9	7,1
	20	24				0,77	6,8	6,3	18,2	10,1	1,3	36	7,3	6,1
S2011122	0	4	3538447,113	7006525,724	128,224	3,53	3,3	7,9	19,7	7,5	0,45	35	9	7,9
	4	8				3,65	3,7	7,8	20,6	7,3	0,38	34	9,7	6,9
	8	12				4,84	9	6,5	17,8	13,5	0,26	28	8,4	5,6
	12	16				5,01	8,6	6,7	18,6	13,6	0,16	29	8,7	5,9
	16	20				5,07	6,3	7,1	19	11,3	0,14	30	8,6	6,4
S2011123	0	4	3538452,686	7006520,509	125,831	5,6	18,7	4,3	14,1	23	0,25	19	6,2	4,3
	4	8				5,9	10,1	6,2	18	14,1	0,23	27	7,7	5,9
	8	12				5,41	10,2	6	17,6	14	0,38	27	8,1	5,9
	12	16				4,95	5,2	7,6	20,3	10	0,19	33	9,3	6,8
	16	20				4,36	2,9	8,4	21,9	8	0,1	35	9,8	7,3
	20	24				4,37	6	7,6	20	10,5	0,2	32	9,2	6,8
S2011124	0	4	3538462,435	7006518,506	126,804	4,56	6,6	7,2	20,1	9,9	0,1	31	9,3	6,5
	4	8				4,98	4,7	7,6	20,4	9,3	0,23	32	10	6,6
	8	12				5,21	5,4	7,3	19,9	10	0,12	31	9,5	6,5
	12	16				5,83	3,7	7,3	19,5	9,8	0,11	31	8,8	6,7
	16	20				4,88	5,4	7,5	20,2	9,9	0,2	32	8,7	7,1
	20	24				4,79	3,5	8,1	20,8	8,3	0,17	34	9,6	7,1
S2011125	0	4	3538472,085	7006513,26	125,807	3,79	1,6	8,4	21,5	6,3	0,12	36	10,5	7,1
	4	8				5,15	16,2	5	15,5	21,1	0,36	22	7,1	4,6
	8	12				4,7	7,1	6,8	19,4	11,9	0,16	31	9,4	6,2
	12	16				4,51	2,8	8,5	21,3	7,2	0,11	35	9,1	7,6
	16	20				4,68	4,7	7,9	20,7	8,8	0,21	33	9	7,1
	20	24				5,72	9,6	6,1	16,9	15,7	0,21	26	7,3	5,7
S2011128	0	4	3538440,244	7006561,924	131	5,89	4,5	7,5	18,8	12	0,25	32	9,1	7,3
	4	8				5,82	3,5	7,7	18,8	10,4	0,2	32	9,2	7,4
	8	12				5,45	7,5	6,7	17,1	14,5	0,31	29	8,2	6,5
	12	16				6,08	12	5,6	14,4	20,4	0,37	25	7,1	5,3
	16	20				4,48	3,1	8	18,7	9,7	0,4	34	8,2	8,2
	20	24				3,3	5,5	5,7	13,5	11,7	2,3	37	8	7,9
S2011129	0	4	3538449,642	7006557,096	131,172	8,47	4	7,3	18,9	13,6	0,11	30	8,6	6,3
	4	8				5,13	4,5	8	19,9	10,3	0,1	32	8,4	7,2
	8	12				1,06	5,2	7,5	18,9	8,9	0,59	36	7	7,8
	12	16				0,44	3,2	7,8	17,6	6,6	0,89	41	6,9	8,4
	16	20				0,33	3,3	8,7	15,5	6,2	0,88	42	6,2	9,7
	20	24				3,76	11,1	5,9	14,1	18,3	0,58	29	6,1	6,1
S2011130	0	4	3538458,135	7006553,92	128,73	6,07	7,1	6,4	18,6	13,5	0,36	29	8,5	6,2
	4	8				6,56	6,1	6,9	18,5	13,1	0,22	29	8,6	6,3
	8	12				6,2	9,2	6,3	17,7	15,2	0,37	27	8,2	6
	12	16				5	2,2	7,3	20,1	8,9	0,35	34	9,8	6,6
	16	20				4,16	4,3	7,7	20,4	8,9	0,29	33	9,3	7
	20	24				4,22	10	6,2	17,1	13,2	0,33	27	7,6	5,8

S2011131	0	4	3538468,545	7006548,714	128,48	5,8	6	6,8	18,1	12,6	0,1	28	9	5,6
	4	8				5,69	4,2	8,3	21,5	10,5	0,11	34	10,3	6,9
	8	12				6,33	4,1	7,3	19,4	10,9	0,1	31	9,5	6
	12	16				6,22	17	4,4	14	23,2	0,17	20	6,6	4,2
	16	20				5,15	8,7	6,5	17,8	13,9	0,16	28	8,3	6,2
	20	24				5,49	7,3	6,4	18,5	12,1	0,33	29	8,4	6,1
S2011132	0	4	3538477,481	7006545,116	127,253	5,97	9,3	6,5	18,4	15,9	0,49	29	8,1	6,4
	4	8				5,01	10,4	6,6	19,4	14,7	0,28	28	6,7	6,6
	8	12				4,97	12,8	6,1	18,5	17,3	0,32	26	6,3	6
	12	16				4,55	11,5	6,9	19,9	14,6	0,33	29	6,7	6,9
	16	20				4,96	8,5	7,1	20	12,7	0,31	30	6,9	7,1
	20	24				4,99	10,4	6,7	19,6	14,5	0,31	29	6,7	6,8
S2011133	0	4	3538485,528	7006540,711	125,712	0,24	3,5	6,6	19,7	7,7	1,1	40	6,4	6,9
	4	8				0,25	3,7	7	19,7	7,1	0,94	38	6,5	7,3
	8	12				0,18	4,9	6,3	21	6,4	1,3	39	6,8	6,2
	12	16				0,27	4	8,5	19,1	6,3	0,6	40	7,4	9,2
	16	20				0,47	3,7	10,3	14,8	5,7	0,37	43	6,5	12,2
	20	24				0,7	3,2	9,5	16,4	6	0,62	43	7	10,6
S2011134	0	4	3538493,495	7006536,487	123,616	0,52	2,9	7,5	18	6	1	40	9,4	7,9
	4	8				0,48	3,3	6,9	18,3	7,1	1,1	39	9,2	7,2
	8	12				3,85	2,2	7,5	20,2	7,5	0,33	34	8,1	7,7
	12	16				4,9	3,8	8	20,4	9,7	0,33	35	7,9	8,3
	16	20				5,12	8,4	7,1	18,6	14	0,38	31	7,3	7,3
	20	24				4,72	6,4	7,7	19,2	12	0,4	33	7,6	7,9
S2011135	0	4	3538444,428	7006593,632	128,819	0,27	9,4	5	23,4	6,8	0,42	35	9,1	4
	4	8				0,13	10	5	24	6,5	0,21	35	9,5	3,5
	8	12				0,13	10,2	5	24,4	6,6	0,1	35	9,5	3,5
	12	16				0,27	10	5,1	24,3	5,9	0,1	36	8,9	3,7
	16	20				0,31	8,5	5,2	23,7	6,1	0,16	36	8,8	4,1
	20	24				0,38	7,4	5,4	24,7	5,5	0,3	37	8,7	4,2
S2011136	0	4	3538453,088	7006589,023	129,466	5,85	4,7	6,8	17,9	12,7	0,57	32	8	7,1
	4	8				4,26	2,8	7,4	18,4	9,4	1,1	37	8,1	8,6
	8	12				4,4	4,3	6,5	17,2	11,6	1,1	35	8,1	6,9
	12	16				2,43	4,6	6,8	17,5	10,3	0,97	37	7,5	7,2
	16	20				0,72	4,2	7,6	18,7	7,8	0,68	38	7,1	8,2
	20	24				0,46	3,4	7,2	19,1	7,2	1	40	7	7,7
S2011137	0	4	3538460,777	7006583,938	128,95	4,95	16,3	4,9	13,1	23,9	0,31	22	5,8	5
	4	8				5,62	5,7	6,5	17	12,9	0,66	31	7,9	6,5
	8	12				6,03	9	6	17,2	16,2	0,4	28	7,5	5,6
	12	16				5,93	3,1	6,8	19,8	9,9	0,29	33	8,2	6,1
	16	20				5,44	5,5	6,8	17,9	11,6	0,32	30	8,5	6,8
	20	24				5,86	10,2	5,8	15,4	17,5	0,37	26	7,2	5,9
S2011138	0	4	3538472,887	7006578,304	127,785	4,96	5,3	7,2	20,7	10,2	0,19	32	8,9	7
	4	8				6,95	2,4	7,7	20,5	10,3	0,1	32	8,7	6,9
	8	12				5,28	10,1	6,4	18	15,5	0,19	27	7,8	6
	12	16				4,84	4,5	7,1	20,2	9,2	0,1	31	8,5	6,6
	16	20				4,58	5,1	7,6	18,1	10,1	0,27	32	7,8	8
	20	24				4,84	6,5	7,2	19,7	10,9	0,18	31	8,7	6,9
S2011139	0	4	3538478,952	7006575,823	128,615	5,62	7,6	6,6	18,4	13,2	0,1	29	8,1	6,4
	4	8				6,95	14,4	4,8	14,9	20,4	0,18	21	7,3	4,7
	8	12				6,91	13,1	6	18,2	20,6	0,36	27	8,3	5,9
	12	16				6,23	7,6	6,7	19,6	13,8	0,31	31	8,7	6,6
	16	20				6,31	5,6	6,7	19,3	12,7	0,28	31	8,5	6,7
	20	24				6,22	10,2	5,6	16,8	17,1	0,33	26	7,7	5,4

S2011140	0	4	3538490,935	7006572,83	126,144	3,8	3,3	7,5	19,1	9,1	0,38	34	8,3	7,8
	4	8				0,77	3,5	7,6	17,9	7	0,99	40	6,9	8
	8	12				0,25	3,3	9,1	16	5,9	0,56	41	6,4	9,9
	12	16				1,32	3,5	9,2	12,4	7,8	0,55	41	7,7	10
	16	20				4,95	3,8	7,1	17,7	11,4	0,71	35	7,9	7,3
	20	24				4,93	6	7,2	18,6	12	0,36	32	7,5	7,3
S2011143	0	4	3538474,803	7006613,096	126,582	4,26	15,1	5,4	16,3	19,1	0,28	24	6,9	5,8
	4	8				5,73	8,1	6	13,9	15,7	0,54	29	6,7	6,6
	8	12				1,46	13,6	6,4	18,6	14,5	0,32	29	7,2	6,9
	12	16				4,52	11,2	5,5	15,3	17,2	0,5	27	7	5,9
	16	20				2,17	18,5	5,2	14,8	21,5	0,32	23	6,2	5,4
	20	24				5,84	14	5,3	14,2	22	0,37	24	6,6	5,4
S2011144	0	4	3538483,625	7006607,546	126,258	4,95	3,2	7	18,8	8,5	0,32	35	8,2	7,5
	4	8				5,53	5,5	7,1	21,4	9,6	0,1	31	8,9	6,6
	8	12				5,41	5,9	6,5	18,9	10,3	0,31	29	8,1	6,4
	12	16				4,56	5,5	7,5	18,9	10,3	0,19	33	8,9	7,8
	16	20				5,73	4,4	7,2	19	10,6	0,42	33	8,4	7,3
	20	24				4,07	9,4	6,5	17,8	12,6	0,48	30	7,9	6,7
S2011146	0	4	3538501,623	7006599,685	125,809	4,81	5,6	7,4	19,5	10,6	0,34	31	7,3	7,5
	4	8				6,09	6,1	6,6	17,7	12,5	0,45	29	7,8	6,7
	8	12				4,12	6,2	7,4	18,9	10,6	0,3	31	6,6	7,9
	12	16				4,75	12,2	5,5	16,3	16,8	0,37	25	6,7	5,8
	16	20				4,98	8	6,3	14,1	13,9	0,53	30	8,6	6,9
	20	24				4,05	8,3	6,5	17,1	13,3	0,29	29	7,7	6,9
S2011147	0	4	3538511,092	7006595,154	124,892	3,69	2,2	8,9	16,2	7,4	0,33	36	6,9	10,5
	4	8				4,43	4,1	7,6	19,1	9,4	0,47	32	7,6	7,7
	8	12				4,22	5	7,3	19,4	9,3	0,55	32	7,6	7,4
	12	16				2,92	4,4	8,7	12,6	8,7	0,69	38	7	10,3
	16	20				3,8	7,4	8,1	15,2	10,2	0,38	35	6,1	9,1
	20	24				4,3	4,1	6,9	17,9	11,4	0,4	30	7,3	7,2

Appendix 2.

Sludge sample locations and analysis results

Saarinen east

sample code	depth from (m)	to (m)	location x	y	z	P205	CO2	K20	MgO	CaO	Na2O	SiO2	Fe2O3	Al2O3
S2011148	0	4	3538515,336	7006394,935	130,316	3,47	6,9	7,6	19	11	0,16	32	7	7,7
	4	8				3,02	5,4	8,2	19,9	8,5	0,15	33	7,7	8,2
	8	12				3,33	6,2	7,8	19	9,8	0,14	32	7,4	7,7
	12	16				2,75	6,7	7,7	19,4	9,7	0,25	32	8,1	7,6
	16	20				3,75	3,7	8,1	19,6	8,4	0,25	33	8,3	7,9
	20	24				3,58	4,5	8	19,5	8,7	0,18	32	8,2	8
S2011149	0	4	3538524,755	7006389,737	130,654	4,88	4,2	7,2	18,5	9,6	0,22	32	7,9	7,6
	4	8				4,14	4,9	7,3	18,8	9,7	0,24	33	7,9	7,8
	8	12				4,21	4,2	7,4	19	9,4	0,26	34	8,2	7,9
	12	16				4,3	3,6	7,3	18,9	8,9	0,28	34	8,2	7,7
	16	20				4,46	3,4	6,9	18,2	10,1	0,37	34	8,1	7,4
	20	24				4,32	3,1	7,3	18,4	9,6	0,25	34	8,2	7,8
S2011150	0	4	3538533,614	7006386,338	131,069	3,92	5,6	6,4	17,6	10,9	0,32	32	8,2	7,3
	4	8				3,62	7,3	6,6	18,5	11,8	0,16	30	7,6	7,2
	8	12				4,05	5	6,6	18,9	9,5	0,39	32	7,7	7,4
	12	16				4,08	8,2	6,4	18,2	12,2	0,23	29	7,5	6,9
	16	20				2,53	7,1	5,7	13,9	10,8	1,5	34	7,3	8,5
	20	24				2,19	10,6	5,8	17	12,9	0,32	28	8	6,4
S2011151	0	4	3538544,686	7006381,273	130,71	0,28	0,1	1,9	14,5	9	1,1	49	9,9	7,8
	4	8				0,26	1,5	2	11,3	7,9	1,5	49	8,2	7,7
	8	12				0,27	2,3	2,7	13,4	9,3	0,58	47	9,4	6,9
	12	16				0,21	2,5	2,9	11,7	8,3	0,76	51	8,4	7,4
	16	20				0,2	1,8	2,7	12,8	8	0,37	51	8,5	6,5
	20	24				0,21	0,9	2,6	13,5	7,6	0,44	53	8,5	6,4
S2011152	0	4	3538553,202	7006377,074	130,135	0,1	0,1	0,8	1,2	1,1	5,8	57	1,9	11,5
	4	8				0,1	0,2	0,5	0,9	2	6,1	60	2,6	12,4
	8	12				0,1	0,1	1,2	1,1	0,7	6,2	66	1,8	13,3
	12	16				0,1	0,1	0,7	0,9	0,6	6,7	63	1,4	12,8
	16	20				0,1	0,3	0,8	1	1,4	6	60	1,6	11,8
	20	24				0,1	0,1	1,7	1	1,4	5,5	58	1,7	12,2
S2011153	0	4	3538511,128	7006427,803	128,989	2,79	7,2	7,6	18,8	11,9	0,23	33	8,3	7,6
	4	8				1,75	6,5	7,7	20,5	9	0,36	36	8,4	7,4
	8	12				1,69	5,7	9,2	7,8	10,3	1,1	48	4,8	10,5
	12	16				1,57	4,8	7,7	18,4	8,5	0,71	39	8,7	7,6
	16	20				0,52	9,3	6,4	17,8	12,8	0,8	35	8,5	6,2
	20	24				1,72	8,1	7,1	18,4	12,1	0,53	34	8,3	6,8
S2011154	0	4	3538519,836	7006425,395	130,968	2,91	11	6,1	20,8	11,4	0,32	29	9	6
	4	8				3,45	8	6,7	19,5	12,6	0,35	31	8,4	6,4
	8	12				1,23	4,9	7,8	21,7	7,2	0,44	36	9,6	7,6
	12	16				2,18	5,2	7,5	20,2	8,7	0,42	34	9,3	7,3
	16	20				1,63	6,9	7,5	19,1	10,3	0,49	34	9	7,2
	20	24				4,61	6,9	6,3	17,6	13,9	0,65	32	8,2	6,1
S2011155	0	4	3538526,94	7006421,911	131,701	4,64	5	7,4	18,2	11,3	0,34	32	8	7,5
	4	8				4,36	5,3	7,6	18,7	10,9	0,33	32	8	7,4
	8	12				3,84	3,9	8,2	19,8	8,5	0,26	34	8,1	8
	12	16				4,33	4	7,8	19,4	9,5	0,38	33	8	7,6
	16	20				4,16	4,8	7,7	19,3	9,6	0,3	33	8	7,6
	20	24				4,66	7,4	7,2	18,5	12,7	0,21	30	7	7,2
S2011156	0	4	3538539,013	7006416,683	131,478	3,93	5,5	7	20	10	0,3	32	7,5	7,4
	4	8				3,67	6,6	7,3	19,3	11	0,26	32	7,4	7,5
	8	12				3,37	7	7,2	18,5	11,6	0,37	32	7,7	7,4
S2011157	0	4	3538547,947	7006412,537	131,597	0,92	6,3	4,7	9,9	9,3	3,5	41	8,9	10,9
	4	8				2,92	6,7	7,1	16,7	10,4	0,5	33	8,8	7,8
	8	12				4,13	3,4	7,8	20,3	8,1	0,15	33	8,5	7,6
	12	16				4,44	6,2	6,9	18,8	11,2	0,27	30	8,8	6,7
	16	20				3,69	4,6	7,5	19,8	9,2	0,29	32	8,8	7,2
	20	24				4,04	5	7,3	19,7	9,7	0,33	32	8,8	7

S2011158	0	4	3538556,209	7006408,281	130,93	0,17	1	2,9	6,1	8,2	1,3	45	15,4	13,1
	4	8				0,13	4,9	4,3	4,6	10,1	0,62	45	13,9	12,4
	8	12				2,15	5,2	3,9	9,3	10,2	2	45	8,2	9,9
	12	16				0,81	5	5,4	4,6	6,5	3,7	50	5,6	12,8
	16	20				0,85	5,4	5,2	6	6,9	3,1	48	6,3	11,6
	20	24				3,24	3,4	6,7	16,1	7,5	0,85	36	8,7	9,5
S2011162	0	4	3538577,844	7006431,01	127,667	0,99	1	2,2	9,5	5,8	3,5	53	7,1	10,9
	4	8				0,68	0,1	1,5	7,6	4,7	3,9	58	6,3	10,3
	8	12				0,35	3	2,8	9,8	8,1	1,9	48	9,4	9,5
	12	16				1,18	4,9	3,8	9,6	9,7	2,3	45	8,7	10,1
	16	20				1,07	4,7	4,3	8,9	7,7	3,8	46	7,4	12,5
	20	24				2,36	3,6	6,3	14,3	7,9	1,8	40	8,9	11,1
S2011163	0	4	3538569,971	7006424,123	129,129	0,55	0,9	2,2	10,4	7,1	2,3	51	8,7	8,8
	4	8				0,24	3,6	3,2	12,8	9,9	0,73	47	9,2	7,6
	8	12				0,1	3,4	3,9	11,3	8,3	1,2	43	9,3	9,2
	12	16				3	6,9	5,9	15,5	12,7	0,52	34	8,1	8,2
	16	20				1,76	6,3	5,1	12	10,7	2,3	45	7,7	10,2
	20	24				1,82	7	6,7	16,3	9,7	1,1	39	7,9	9,8
S2011164	0	4	3538559,416	7006435,367	129,491	4,27	4,6	7,9	20,5	9	0,19	34	9,1	7,6
	4	8				4,34	6,4	7,4	19,4	11,5	0,2	32	8,9	7,1
	8	12				5,31	5,2	7,4	19,1	11,4	0,3	33	8,8	7
	12	16				5,87	3,4	7,7	19,7	10,1	0,22	33	8,9	7,2
	16	20				5,22	6	7,2	18,3	12,4	0,28	32	8,4	7,2
	20	24				4,73	5,4	7,5	20,1	9,7	0,32	33	9	7,2
S2011165	0	4	3538550,019	7006441,27	129,314	4,26	6,2	7,6	19,7	11,1	0,2	33	8,2	7,7
	4	8				3,85	7,8	7,5	20,2	10,8	0,2	32	8,1	7,4
	8	12				7,89	8,4	6,3	17,1	16,9	0,1	27	7,2	6,3
	12	16				5,11	17,4	4,8	13,3	26,2	0,2	21	6	4,8
	16	20				4,78	11,7	6,1	17,1	17,3	0,2	27	6,8	6,2
	20	24				4,75	13	5,9	16,9	18,2	0,18	26	6,5	6
S2011166	0	4	3538540,009	7006443,113	128,884	0,1	38,1	1,5	5,4	42,9	0,1	6	2,8	1,5
	4	8				0,1	40,7	0,9	4,9	44,3	0,1	4,3	3	0,9
	8	12				0,1	38,9	1,3	5	43,3	0,13	5,8	3,3	1,3
	12	16				0,1	35,4	1,8	6,3	39,7	0,1	8	4,9	1,8
	16	20				0,1	39,2	1	5,6	42,7	0,16	5,6	4,2	1
	20	24				0,1	27,8	3,2	10	32,3	0,24	14	5,4	3,2
S2011167	0	4	3538532,859	7006450,941	128,81	3,19	8,1	6,8	19,8	11,6	0,28	32	8,9	6,2
	4	8				3,28	8,1	7,2	20,9	10,3	0,1	31	8,9	6,5
	8	12				1,51	6,3	8,1	21,8	7,4	0,19	35	9,1	7,5
	12	16				2,15	8,1	7,2	19,7	10,8	0,24	31	8,3	6,7
	16	20				1,43	7,6	7,6	20,2	9,1	0,33	34	8,5	7,1
	20	24				0,43	4,4	7,6	20	8,5	0,61	36	8,6	7,1
S2011168	0	4	3538525,119	7006456,672	127,863	4,2	5,7	6,5	17,8	12,8	0,86	35	8,1	6,3
	4	8				3,37	5,5	7,2	18,9	10,5	0,51	34	9,3	6,8
	8	12				0,93	8,1	8,2	22	7,5	0,12	34	9,1	7,8
	12	16				2,23	8,9	6,5	22	9,3	0,29	32	9,5	5,8
	16	20				0,75	7,2	7	20,8	8,1	0,63	35	9,1	6,3
	20	24				0,46	4,7	8,4	22,9	4,3	0,19	36	9,6	7,3
S2011169	0	4	3538516,227	7006464,98	127,151	1,25	4,9	7,7	19,8	8	0,7	36	8,9	7,5
	4	8				4,22	3	7,3	19,3	8,9	0,65	35	8,8	6,9
	8	12				4,39	6	6,9	18,2	11,9	0,57	32	8,3	6,5
	12	16				4,69	5	7,2	18,2	11,5	0,57	33	8,8	6,8
	16	20				4,12	4,4	7	16,2	11,3	1,1	36	7,9	7,4
	20	24				4,52	4,8	7,2	17,4	11,9	0,68	34	8,8	7,5
S2011170	0	4	3538517,724	7006488,432	126,942	2,33	4,9	7,1	18	9,2	1,1	37	8	8,2
	4	8				2,38	4	7,1	19,3	8,3	1	38	8,3	7,4
	8	12				2,09	6,9	6,6	18,5	10,6	0,94	36	8,4	6,6

Appendix 3
Sludge drilling field observations

Rock type abbreviations:
DB=diabase, Fen=fenite, PURU=reddish brown (ore)
TURU=dark brown (ore), MURU=blackish (ore), KB=carbonatite

WEST SAARINEN

Profile	Drillhole (date)	metres	rock types				
			1	2	3	4	
2	**106**	0-4	DB	"	"	"	
	17.6.	4-8	DB	"	"	Turu	Lighter than DB but not similar to Fen
		8-12	DB	"	"	"	Very fine and dusty. larger grains along
		12-16	DB	"	"	"	
		16-20	DB	"	"	"	
		20-24	DB	"	"	Turu	
	107	0-4	Puru/KB	"	"	"	
	17.6.	4-8	Puru/KB	KB	"	"	
		8-12	Turu	"	"	"	
		12-16	Turu	KB	"	"	
		16-20	KB	"	"	Turu	
		20-24	Turu	"	"	"	
3	**112**	0-4	Turu	"	"	"	Very fine
	17.6.	4-8	Turu	"	"	"	
		8-12	Turu	"	"	"	
		12-16	Turu	"	"	"	
		16-20	Turu	"	Turu/KB	"	
		20-24	Turu/KB	"	"	"	
	113	0-4	Turu	"	"	"	Very fine
	17.6.	4-8	Puru	"	Turu	"	
		8-12	Turu/KB	"	"	"	
		12-16	Turu	KB	Turu	"	
		16-20	Turu	"	"	"	
		20-24	Puru/KB	"	Turu	"	
	114	0-4	Puru	Turu/KB	"	"	
	16.6.	4-8	Muru	"	"	"	
		8-12	Muru	Fen	Muru	Muru/KB	A little fenitic. maybe a xenolith?
		12-16	Muru	"	"	"	
		16-20	Turu	"	"	"	Very fine. moist
		20-24	Turu	"	"	"	moist
	115	0-4	Turu	"	Puru	"	
	16.6.	4-8	Puru	"	"	"	
		8-12	Turu	Puru	"	"	
		12-16	Turu	Puru	"	"	
		16-20	Puru	"	"	"	A little finer than previous
		20-24	Puru	"	"	Turu	
	116	0-4	Turu/KB	"	Turu	"	
	16.6.	4-8	Turu	"	Turu/KB	"	
		8-12	Turu	"	Turu/KB	"	
		12-16	Turu/KB	"	"	"	
		16-20	Turu	Fen	"	"	
		20-24	Fen	"	"	Turu	
4	**119**	0-4	Fen	"	"	"	first 2 metres finer. 3-4m coarser
	17.6.	4-8	Fen	"	DB	"	
		8-12	DB	"	"	Fen	
		12-16	DB	Fen	DB	Fen	
		16-20	DB	"	Fen	"	DB finer than previous
		20-24	Fen	"	DB	"	
	120	0-4	Turu	"	"	"	Very fine
	17.6.	4-8	Turu	Puru	"	"	
		8-12	KB	Puru	"	"	Fine
		12-16	Puru/KB	Turu	"	"	Fine
		16-20	Turu/KB	"	Turu	"	20 and 21 m moist
		20-24	Turu	"	"	"	moist. small sample size
	121	0-4	Turu	"	"	"	
	17.6.	4-8	Turu	"	"	"	
		8-12	Turu	"	"	"	
		12-16	Turu	"	"	"	
		16-20	Turu	"	"	"	20 and 21 m moist
		20-24	Turu	"	"	"	moist

122	0-4	Turu	"	"	"	
16.6.	4-8	Turu	"	"	"	
	8-12	Turu	"	"	"	finer. feels moist
	12-16	Turu	"	"	"	moist
	16-20	Turu	"	"	"	damp. small sample size
	20-24					water
123	0-4	KB	"	"	Turu	
16.6.	4-8	Turu	"	"	"	
	8-12	Turu	"	"	"	
	12-16	Turu	"	"	"	14 and 15 m coarser
	16-20	Turu	"	"	"	
	20-24	Puru	"	Turu	"	
124	0-4	Turu	"	"	"	coarse
16.6.	4-8	Turu	"	"	"	"
	8-12	Turu	"	"	"	"
	12-16	Turu	"	"	"	A little finer than previous
	16-20	Turu	"	"	"	
	20-24	Turu	"	"	"	
125	0-4	Turu	"	"	"	
16.6.	4-8	Turu/KB	"	"	"	
	8-12	Turu	"	"	"	
	12-16	Turu	"	"	"	sheared
	16-20	Turu	"	"	"	
	20-24	Turu	"	"	"	A little finer than previous
128	0-4	Turu/KB	"	"	"	
29.6.	4-8	"	"	Turu	"	
	8-12	Turu/KB	"	Turu	"	
	12-16	"	"	"	"	
	16-20	"	"	"	"	
	20-24	"	"	"	"	
129	0-4	Puru/KB	Puru	"	"	
29.6.	4-8	Puru/KB	Puru	"	"	
	8-12	Turu	"	"	"	sheared
	12-16	"	"	"	"	sheared
	16-20	"	"	"	"	sheared
	20-24	"	"	Turu/KB	"	
130	0-4	Turu	"	"	Puru	
29.6.	4-8	Puru/KB	Puru	"	Turu	
	8-12	Turu/KB	Turu	"	Puru	
	12-16	"	"	"	"	
	16-20	"	"	"	"	
	20-24	Turu/KB	"	Puru	"	
131	0-4	KB	"	Puru	"	
29.6.	4-8	"	"	"	"	
	8-12	"	"	"	"	
	12-16	"	"	"	Turu/KB	
	16-20	"	"	"	Puru	
	20-24	Turu	"	"	"	
132	0-4	Turu	"	"	"	
29.6.	4-8	"	"	"	"	
	8-12	"	"	"	"	
	12-16	"	"	"	"	fine
	16-20	"	"	"	"	
	20-24	"	"	"	"	
133	0-4	Turu	"	"	"	sheared
29.6.	4-8	"	"	"	"	
	8-12	"	"	"	"	
	12-16	"	"	"	"	little moist
	16-20	"	"	"	"	little coarser (not sheared anymore)
	20-24	"	"	"	"	"
134	0-4	Turu	"	"	"	sheared
29.6.	4-8	"	"	"	"	
	8-12	"	"	"	"	moist
	12-16	"	"	"	"	more moist
	16-20	"	"	"	"	"
	20-24	"	"	"	"	"

6	**135**	0-4	Sivuk.	"	"	"	Altered side rock
	28.6.	4-8	"	"	"	"	
		8-12	"	"	"	"	
		12-16	"	"	"	"	
		16-20	"	"	"	"	
		20-24	"	"	"	"	
	136	0-4	Turu	"	"	"	
	29.6.	4-8	"	"	"	"	sheared
		8-12	"	"	"	"	sheared
		12-16	"	"	"	"	sheared
		16-20	"	"	"	"	sheared
		20-24	"	"	"	"	sheared
	137	0-4	Turu/KB	"	"	"	
	28.6.	4-8	Turu	"	"	Puru	
		8-12	Turu/KB	Puru	"	"	
		12-16	"	"	"	"	
		16-20	Turu	"	"	"	
		20-24	Turu/KB	"	"	"	
	138	0-4	Turu/KB	"	"	"	
	29.6.	4-8	Turu	"	"	"	
		8-12	"	"	Turu/KB	"	
		12-16	Turu	"	"	"	
		16-20	"	"	"	"	
		20-24	"	"	"	"	
	139	0-4	Turu/KB	"	"	"	
	29.6.	4-8	"	"	"	"	
		8-12	Turu	"	"	"	10 and 11 m sheared
		12-16	Turu/KB	"	Turu	"	
		16-20	"	"	"	"	
		20-24	Turu/KB	Turu	"	"	
	140	0-4	Turu	"	"	"	
	28.6.	4-8	Turu/KB	"	"	"	
		8-12	Turu	"	"	"	
		12-16	"	"	"	"	little moist
		16-20	"	"	"	"	fine
		20-24	"	"	"	"	
7	**143**	0-4	Turu/KB	"	"	"	
	28.6.	4-8	"	"	Turu	"	
		8-12	"	Turu/KB	"	Turu	
		12-16	"	"	"	"	
		16-20	"	Turu/KB	"	Turu	
		20-24	Turu/KB	"	"	Turu	
	144	0-4	Turu/KB	"	Turu	"	
	28.6.	4-8	Turu/KB	"	"	"	
		8-12	"	Turu	"	"	
		12-16	"	"	"	"	
		16-20	"	"	"	"	
		20-24	"	"	"	"	
	146	0-4	Turu/KB	Turu	"	"	
	28.6.	4-8	"	"	"	"	
		8-12	Turu/KB	Turu	"	"	
		12-16	"	"	"	"	
		16-20	"	"	"	"	
		20-24	"	"	"	"	
	147	0-4	Turu/KB	"	Turu	"	
	28.6.	4-8	"	"	"	"	
		8-12	"	"	"	"	
		12-16	"	"	"	Fen	
		16-20	Turu	"	"	"	
		20-24	"	"	"	"	

Appendix 4
Sludge drilling field observations

Rock type abbreviations:
DB=diabase, Fen=fenite, PURU=reddish brown (ore)
TURU=dark brown (ore), MURU=blackish (ore), KB=carbonatite

EAST SAARINEN

Profile	**Drillhole** (date. 7.9.)	**metres**	rock types				
			1	2	3	4	
1	**148**	0-4	Turu	"	"	"	coarse mica
		4-8	"	"	"	"	little more crb
		8-12	"	"	"	"	little more crb, mica in aggregates
		12-16	"	"	"	"	
		16-20	"	"	"	"	
		20-24	"	"	"	"	
	149	0-4	Turu	"	"	"	
		4-8	"	"	"	"	little more crb
		8-12	"	"	"	"	"
		12-16	"	"	"	"	coarser mica
		16-20	"	"	"	"	18 and 19 m little wet
		20-24	"	"	"	"	more wet
	150	0-4	Muru	Turu	"	"	muru coarse, turu finer
		4-8	"	"	"	"	little wet
		8-12	"	"	"	"	"
		12-16	"	"	"	"	less wet
		16-20	"	"	"	"	drier, more crb
		20-24	"	"	"	"	"
	151	0-4	DB	"	"	"	couple of grains of crb
		4-8	"	"	"	"	"
		8-12	"	"	"	"	"
		12-16	"	"	"	"	"
		16-20	"	"	"	"	"
		20-24	"	"	"	"	"
	152	0-4	Gneissi	"	"	"	grey
		4-8	"	"	"	"	"
		8-12	"	"	"	"	"
		12-16	"	"	"	"	little browner
		16-20	"	"	"	"	one sample went wrong,
		20-24	"	"	"	"	more sludge after 6th
2	**153**	0-4	Turu	"	"	"	coarse mica
		4-8	"	"	"	"	
		8-12	"	CRB	"	"	
		12-16	Turu	"	"	"	
		16-20	"	"	"	"	
		20-24	"	"	"	"	
	154	0-4	KGL	"	"	"	coarse
		4-8	"	"	"	"	large aggregates
		8-12	"	"	"	"	some aggregates maybe amphibole?
		12-16	"	"	"	"	coarser mica, no other minerals
		16-20	"	"	"	"	
		20-24	"	"	"	"	
	155	0-4	Turu	"	"	"	little wet, fine grained
		4-8	"	"	"	"	finer than previous
		8-12	"	"	"	"	"
		12-16	"	"	"	"	"
		16-20	"	"	"	"	finer
		20-24	"	"	"	"	
	156	0-4	Turu	"	"	"	
		4-8	"	"	"	"	6 and 7 m more wet
		8-12	"	"	"	"	
		12-16	VESI				WATER HOLE
		16-20					
		20-24					
	157	0-4	DR	"	"	"	These rocks in the gradual contact zone!
		4-8	"	Puru	"	"	little more mica
		8-12	"	"	"	"	
		12-16	"	"	"	"	
		16-20	"	"	"	"	
		20-24	"	"	"	"	

158	0-4	DB	"	"	"	Amp-rich zone
	4-8	"	"	"	"	more coarse rocks than in 151
	8-12	"	"	"	"	contact zone
	12-16	DR	"	"	"	dark, coarser dioritic, also light grains
	16-20	"	"	"	"	
	20-24	DB	"	"	"	dark brown, no grains, very fine
162	0-4	DB	"	"	"	gradual contact zone!
	4-8	"	"	"	"	probably not pure DB -- amp-rich
	8-12	"	"	"	"	wet
	12-16	"	"	"	"	"
	16-20	"	"	"	"	"
	20-24	"	"	"	"	"
163	0-4	DB	"	"	"	gradual contact zone
	4-8	"	"	"	"	
	8-12	"	"	"	"	
	12-16	"	"	"	"	wet
	16-20	"	"	"	"	more wet
	20-24	"	"	"	"	
164	0-4	Turu	"	"	"	medium coarse
	4-8	"	"	"	"	6 and 7 m a little wet
	8-12	"	"	"	"	little wet
	12-16	"	"	"	"	"
	16-20	"	"	"	"	fine
	20-24	"	"	"	"	fine
165	0-4	Turu	"	"	"	medium
	4-8	"	"	"	"	
	8-12	"	"	"	"	little finer
	12-16	"	"	"	"	little more fine, more crb
	16-20	"	"	"	"	very fine
	20-24	"	"	"	"	"
166	0-4	CRB	"	"	"	
	4-8	"	"	"	"	
	8-12	"	"	"	"	
	12-16	"	"	"	"	
	16-20	"	"	"	"	18 and 19 m more mica
	20-24	"	"	"	"	more mica
167	0-4	KGL	"	"	"	
	4-8	"	"	"	"	Puru grains (aggregates)
	8-12	"	"	"	"	
	12-16	"	"	"	"	more crb
	16-20	"	"	"	"	less crb
	20-24	Turu	"	"	"	coarse mica
168	0-4	Turu	"	"	"	
	4-8	"	"	"	"	
	8-12	"	"	"	"	coarse
	12-16	"	"	"	"	
	16-20	"	"	"	"	little more crb
	20-24	"	"	"	"	coarser than previous, less crb
169	0-4	Turu	"	"	"	little wet
	4-8	"	"	"	"	"
	8-12	"	"	"	"	"
	12-16	"	"	"	"	"
	16-20	"	Muru	"	"	fine
	20-24	Turu	"	"	"	very fine
4 **170**	0-4	Muru	"	"	"	a little crb
	4-8	"	"	"	"	6 and 7 m more wet
	8-12	"	"	"	"	wet
	12-16	VESI				water
	16-20					
	20-24					